THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

May 1983

Met.O.958 No. 1330 Vol. 112

METEOROLOGICAL OFFICE Met.O.958

THE METEOROLOGICAL MAGAZINE

No. 1330, May 1983, Vol. 112

551.5:06:551.510.522

The work of the Boundary Layer Branch of the Meteorological Office

By C. J. Readings
(Chief Meteorological Officer, Meteorological Research Flight, Farnborough)

P. J. Mason
(Meteorological Office, RAF Cardington)

and F. B. Smith
(Meteorological Office, Bracknell)

Summary

An account is given of work performed during the last few years comprising (a) observational studies of the boundary layer over flat surfaces including the effects of cloud and stable atmospheric stratification and the special characteristics of flow over the sea, (b) observations of flow over hills and valleys including Ailsa Craig and the Sirhowy Valley, (c) theoretical studies of two-level flow relevant to (a) and (b), and (d) observational and theoretical studies of the dispersion of atmospheric pollutants on all scales.

Introduction

The boundary layer — roughly speaking the lowest kilometre of the atmosphere — is important for many reasons. It provides the immediate environment for many human activities and is of direct consequence to pollution dispersal, structural loading and so on. However, in addition, by bringing about the transfer of heat, momentum and moisture between the earth's surface and the atmosphere above, it plays a large part in determining the properties of weather and atmospheric motion systems on all scales and hence is of more general meteorological importance. The importance of the boundary layer and the gaps in our knowledge of it have long been appreciated by the meteorological community as a whole and over the last decade there have been several large international experiments aimed at furthering our understanding of this part of the atmosphere; notable among these are the Minnesota Experiment, the GARP Atlantic Tropical Experiment (GATE) and the Joint Air–Sea Interaction (JASIN) experiment. The Office has made (and continues to make) major contributions to this work, both over land using the tethered-balloon facility based at Cardington, Bedfordshire, and over the sea using the instrumented aircraft of the Meteorological Research Flight.

The aim of boundary-layer work is to be able to calculate — and hence predict — the properties and effects of the layer both on the large scale, affecting transfers between earth and atmosphere, and on the local scale, where they determine such things as the wind speed at the crest of a particular hill or the pollution in a particular configuration of valleys. The difficulties of this work are exacerbated by the

wide range of scales of motion involved, from the large-scale changes of airflow caused by changing weather systems, or by hills or coasts, to the small-scale eddies caused by blades of grass. The boundary layer is, almost by definition, the region where motions on all these scales interact and no one scale can be treated in isolation from the others. It is, in practical terms, impossible to calculate motions on a wide range of scales simultaneously at the same level of detail. Progress is made by setting up mathematical representations ('models') which reproduce the scale of major interest faithfully and which represent the other scales by means of various simplifications or approximations. The theoretical modelling work, of course, has to go hand in hand with corresponding experimental work to check the adequacy of the models in different situations and suggest ways of improving them where they are inadequate. The required measurements — again involving motions on many different scales — are by no means easy, and improved measuring techniques are still needed in some areas.

Despite many years of work our knowledge of the boundary layer is reasonably satisfactory only for the simplest of situations, namely over flat uniform land with a dry atmosphere that is neutral or slightly unstable. In the presence of clouds, over the sea, over hilly terrain or in stable inversion conditions there is a great lack of good observational data and of models which can represent and predict the phenomena at all adequately. Our current program of work is directed to collecting data and setting up models to cover a wide range of practical situations reasonably well, rather than to refining and perfecting models for the idealized case of flat uniform land and a simple atmosphere. However, in moving towards more realistic conditions, it is important to take one step at a time. Thus, in considering flow over hills and valleys, effort has initially been concentrated on isolated hills of smooth and simple shape rather than the complex geographic features normally met in practice.

Airflow and turbulence within the boundary layer are of course of direct relevance to the dispersion of airborne pollutants. Originally work in dispersion was motivated by an interest in chemical warfare arising out of the First World War. Experiments were carried out over short distances of travel in nearly steady, mostly neutral conditions. The classical diffusion equation provided a theoretical backing but only in the simplest cases. This and subsequent work led to the adoption of the Gaussian plume model which, even today, seems reasonably adequate for many purposes, though attempts to refine it and apply it to complex situations have continued. On the somewhat larger scale, interest in the long-range transport of pollutants received a stimulus from the suggestion that pollutants released by distant sources, notably power-stations, might make important contributions to the increased acidity of rain in certain parts of the world.

This article attempts to review the current interests of the Boundary Layer Branch, seeking to demonstrate the wide range of topics that have to be covered if the needs of customers of the Meteorological Office are to be met. The work is considered under three main headings: firstly the extension of earlier work on boundary layers over flat land to include the effects of cloud, the effects of stable atmospheric stratification and effects occurring over the sea; secondly, work on flow over hills and valleys; and thirdly, work on the dispersion of pollutants in the atmosphere.

The boundary layer over flat surfaces

Introduction

A clear understanding of the structure of quite simple atmospheric boundary layers is basic to progress in more complex areas or actual applications. A distinction must be drawn between observations made over land and those made over the sea. The former are subject to large diurnal variations in the flux of heat energy (which is responsible for the generation of turbulence through buoyancy), normally associated with convective activity in daytime and stable conditions at night.

Conditions over the sea are more constant and heat fluxes generally smaller, with fluxes of water vapour being of more consequence. The surface of the sea is also 'smoother' than the land. These differences are of fundamental importance to theoretical treatments.

A further point worth stressing is the paucity of data above the near-surface layer. Experimental techniques for adequate studies of the atmospheric boundary layer well above the surface have only recently become available, so the bulk of the data available to theoreticians relates to the first ten metres of the atmosphere.

Over land

In the early seventies the Branch was prominent in pioneering detailed studies of the whole (as opposed to just the near-surface) atmospheric boundary layer, using the tethered-balloon facility at Cardington as a platform on which to mount instruments capable of measuring the turbulence structure of the atmosphere. Some of this work was undertaken in collaboration with the Boundary Layer Group at the Air Force Cambridge Research Laboratories, Bedford, Massachusetts, who provided high-quality surface data needed to complement those recorded up to heights of about 2000 metres by the turbulence probes flown from the tethering cable of a kite balloon. This culminated in the Minnesota Experiment, in which the two groups combined their resources to study the structure of the atmospheric boundary layer over an extensive flat plain. Papers based on these data have significantly advanced our knowledge of the atmospheric boundary layer by providing, for the first time, detailed information covering its full depth. Thus, for example, it showed how energy is transferred between the surface and the 'free' atmosphere, how mixing varies with height, how some of our basic theoretical ideas need to be modified if they are to be applied above the surface layer, and so on (Kaimal *et al.*, 1976).

At home, the Branch carried out detailed studies of the way the dissipation of velocity and temperature fluctuations varied with height (Rayment, 1973; Caughey and Rayment, 1974), as well as collaborating with the radar group at Malvern in studying the evolution and erosion of overhead inversions (Palmer *et al.*, 1979; Rayment and Readings, 1974) and with several University groups in studying the development of the convective boundary layer (Moores *et al.*, 1979). More recently the Branch, in collaboration with University College, London, has used an acoustic radar to study the structure of the atmospheric boundary layer (Caughey *et al.*, 1980; Cole *et al.*, 1980). Some of the findings from this work are directly applicable to the forecasting of fog and stratocumulus and a simple acoustic sounder is at present being tested operationally.

Current interest centres on the role of clouds in the atmospheric boundary layer and on stable conditions. Most previous work over land has been concerned with clear boundary layers, despite the prevalence of cloud which can radically alter the characteristics of the atmospheric boundary layer, mainly by providing new sources or sinks of energy. The Branch has started to tackle this topic by considering the measurement of one of the most important parameters, namely the buoyancy, in the presence of cloud. Problems arise because of the difficulty of measuring temperature in the presence of cloud when the temperature sensors become wet. One solution is to measure the total water content together with the wet-bulb temperature. This enables measures of temperature, water vapour and liquid water content to be derived. To this end an instrument based on a commercial Lyman-Alpha hygrometer is being developed, in which liquid water is vaporized before being measured. Preliminary work suggests that an accuracy in temperature of about ± 0.1 °C is attainable, which is quite adequate for the present purposes.

The Branch is also concerned with the structure of stably stratified boundary layers and early last year a limited experimental study of nocturnal boundary layers was mounted in the Fens. During this study, arrays of anemometers and thermometers, together with a sonic anemometer and a new 'mean value' probe, were set up at a site near March, Cambridgeshire. This is a fairly flat site, unlike Cardington (the

site of previous studies — Caughey and Readings, 1975) which is strongly influenced by local ridges. The data should help provide some clear insights into the basic nature of these types of boundary layer, notably their spatial characteristics. This is very important when considering such things as the diurnal evolution of the convective boundary layer, the transitions at sunrise and sunset, fog formation and the spread of pollutants.

In support of this work the Branch is developing an improved instrument to study turbulence structure (and hence mixing and energy transfers), for use in conjunction with the tethered-balloon facility, which will be more flexible, lighter and more accurate than the existing devices. The instrument will take the form of a freely moving vane attached to the tethering cable of the balloon. Velocities relative to the vane will be measured with fast-response propellor anemometers and hot-film sensors, while a magnetometer and some inclinometers will be used to determine the orientation of the vane. Other sensors will monitor temperature, wet-bulb temperature and pressure. The data will be relayed to the ground by radio telemetry where they will be recorded by a computer-based data-acquisition system. This instrument is derived from the 'mean value' instrument which was developed in recent years and has been operated successfully in the field for over a year. An essential difference in the new instrument is the use of fast-response sensors.

It is intended to fly up to ten of the new instruments simultaneously on one cable, so as to make detailed studies of vertical structure, notably in the vicinity of clouds or an inversion. They will complement the facilities provided by the instrumented Hercules aircraft of the Meteorological Research Flight (MRF). The Branch is also considering the use of kites to supplement the tethered-balloon facility.

Over sea

As indicated above, there are substantial differences between atmospheric boundary layers over land and sea, reflecting differences in the basic parameters. Over the years considerable effort has been devoted to the study of the lower atmosphere over the sea using the tools available, notably the instrumented Hercules aircraft of the MRF and tethered balloons. Both facilities were used in GATE (Nicholls and LeMone, 1980; Barnes *et al.*, 1980; Thompson *et al.*, 1980). Current interest centres on JASIN, flights near Britain and KONTUR.

JASIN was a field experiment to study the interaction of the atmospheric and oceanic boundary layers. Proposed some 10 years ago by the Royal Meteorological Society and the Royal Society, it finally reached its climax with two months of intensive operations in the vicinity of Rockall during the summer of 1978, with ships and aircraft of several nations participating. The Office's contribution consisted of the instrumented Hercules aircraft from the MRF and surface instrumentation on three ships, one of which (HMS *Hecla*) served as the base for staff from the Branch who made radiosonde ascents and flew tethered-balloon turbulence probes, as well as supporting an instrumented toroidal buoy. The enormous task of data analysis is not yet complete, but initial results confirm that JASIN should provide valuable insights into the transformations of energy and the mixing processes, as well as providing some information on the role of clouds (especially the coupling between cloudy layers and well-mixed clear regions beneath them). Particularly encouraging has been the wealth of data provided by the Hercules aircraft, which are of sufficient quality to be able to infer wind divergence, geostrophic wind, etc. as well as the more usual meteorological variables, wind, temperature and humidity; this makes it possible to relate detailed structure to large-scale developments.

Separately from JASIN, the Hercules aircraft has been used to study the structure of the atmospheric boundary layer in sea areas around the British Isles in a wide range of stability conditions. Initial work concentrating on the lower levels of the atmosphere has already been published (Nicholls and Readings, 1979, 1981; Nicholls, 1978). Even though these data do not include surface measurements, several

interesting points have already emerged, notably significant differences between 'across wind' and 'along wind' structure and the contrasts between this type of boundary layer and that encountered over land. This work is at present being extended to cover the whole boundary layer, using data gathered during the last few years.

However, work of this nature, involving a single aircraft with no supporting data, will never provide all the information needed and it is desirable to mount more comprehensive experiments specifically designed to concentrate on particular aspects: the latest of these is KONTUR (KONvektion und TURbulenz). This is a study of convective boundary layers which took place in autumn 1981 in the German Bight. Several German research institutes combined to provide extensive surface instrumentation, radiosonde stations, an aircraft and the central organization. The Office's participation was limited to one aircraft, the MRF Hercules. Although data analysis has only just started it is clear that the experiment will complement JASIN by providing data on convective, as opposed to neutral and stable, boundary layers. Several cases where mesoscale organization (e.g. cloud streets) was observed should prove particularly interesting. Both the Cloud Physics Branch and the Meteorological Research Flight are collaborating with the Boundary Layer Branch in this work.

Theoretical work on uniform boundary layers

In order to understand and extend experimental findings and help identify definitive experiments it is necessary to develop relevant theoretical models. Thus, concurrently with the Minnesota experiments and the studies of convective boundary layers (see above), the Branch developed simple analytic models capable of representing broad features of this type of boundary layer (Carson, 1973). In recent years more advanced models capable of representing many more of the features observed in boundary layers have been developed.

Current models depend on separating the spectrum of eddy motions in the atmosphere into two parts, 'large' eddies which are represented explicitly and in detail and 'small' eddies whose effects are represented in a simplified, averaged way. Initial work concentrated on dry neutral boundary layers in which the only types of 'large' eddy represented were long rolls (vortices) with horizontal axes. Such rolls are not uncommon in the atmosphere, particularly over the sea. Results (Mason and Sykes, 1980) depend markedly on the orientation of the rolls with respect to the wind. Another interesting feature is the presence of slow variations on a time-scale of many hours (the Coriolis scale).

The model has been extended to include buoyancy and has already been used to simulate dry convective boundary layers with overhead inversions. The results (which have not yet been published) are very encouraging, reproducing many of the features associated with these types of boundary layer and providing useful insights into the physical processes that occur (see Fig. 1). One notable finding is the dependence of the generation of internal gravity waves, in the stable region above the boundary layer, on the orientation of the rolls.

At present, the model is also being used in a study of stable boundary layers and already it has produced instabilities reminiscent of the 'resonant over-reflection mode' proposed by Davis and Peltier (1980). In this, energy from 'Kelvin–Helmholtz' breakdown is fed into long waves which grow in amplitude, the energy being trapped between the surface and a region of low Richardson number above. Further insights into this and other phenomena affecting the structure of stable boundary layers will no doubt also appear when the model is used to help interpret data from the Fens experiment.

Recently, this two-dimensional model has been further extended to include water (liquid and vapour phases) and it is currently being used to study the structure of cloudy boundary layers. Furthermore, the basic model is being extended to three dimensions, for runs to be conducted on the Meteorological Office's new CYBER 205 computer.

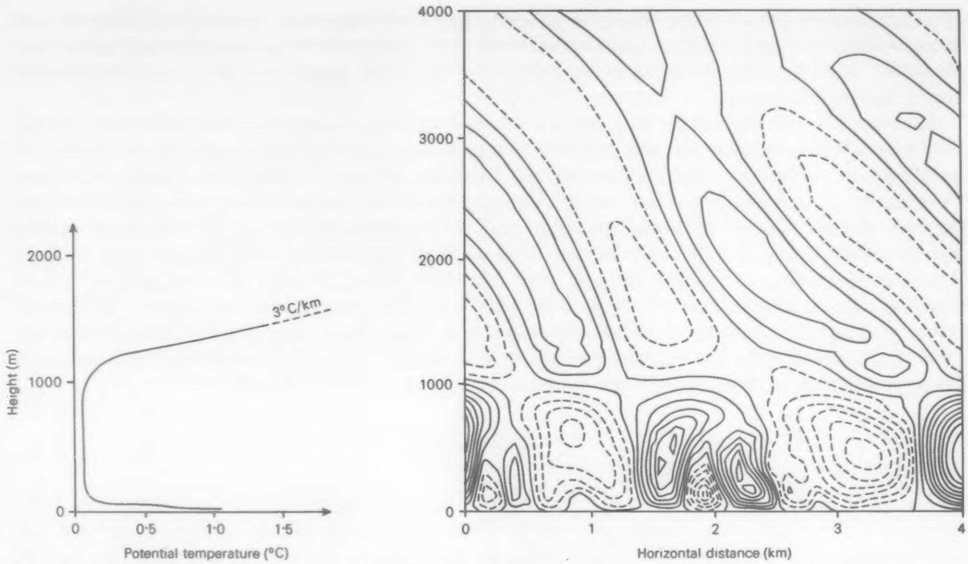


Figure 1. Eddies in and above a dry boundary layer. The main diagram shows results from a two-dimensional model of airflow in a dry boundary layer, with the temperature profile shown in the left-hand diagram. The lines in the diagram are contours of vertical velocity, with a spacing of 10 cm s^{-1}; solid lines represent upward motion, dashed lines downward motion.

Flow over hills and valleys

Introduction

Many practical problems, including wind stresses on buildings, the selection of sites for the use of wind power, the dispersion of pollutants and the safety of aircraft require a knowledge of how wind velocities and turbulence are affected by hills. There is surprisingly little quantitative information on this; measurements of the wind velocity distribution for specific sites on hills are not uncommon, but until quite recently there have been few attempts to relate them to general characteristics such as height, slope, etc. Almost nothing is known about the turbulence characteristics of such flows. A few years ago the Branch began a series of experiments and theoretical studies, beginning with simple shapes of hills, intended to improve our ability to give practical advice.

Experimental program

The first set of field experiments carried out was on Brent Knoll, a roughly circular hill about 140 metres high, situated in Somerset. This is fairly smooth and quite isolated, with slopes of about 1:5 — rather large for comparisons with simple theory but having the advantage of giving easily measured changes. Wind speeds above the ground were measured at various sites and the data compared with the predictions from a generalized form of the Jackson and Hunt theory (Mason and Sykes, 1979b). The theory was found to give reasonable predictions of the observed velocities; in particular the speed-up at the crest was observed to be about 2.3 compared to a theoretical value of 2.0.

Following this preliminary work, a more ambitious study was undertaken of flow over a nearly circular and isolated hill steep enough to produce flow separation. The site chosen for this work was the island of Ailsa Craig off the coast of Ayrshire, south-west Scotland. This island has a height of 330 metres and, apart from cliffs along the western and southern sides, the terrain has slopes of about 30 to 45°. The object of this experiment was to obtain as full a picture as possible of the three-dimensional flow field under conditions of near-neutral stability. Three types of measurement system were used: anemographs to measure mean wind at 4 metres, turbulence probes supported by a tethered-balloon system giving vertical profile information and the instrumented Hercules aircraft from the MRF giving velocities both upwind and downwind of the island.

The anemographs produced a coherent picture of flow round the island showing reversed flow and separation on the downstream side. Data from the balloon-borne probes indicated that the turbulence structure was highly distorted, with large increases in the cross-wind component of turbulence energy. Aircraft observations revealed a very powerful trailing vortex downstream of the obstacle with its axis orientated along the upstream wind direction, and circulation velocities of the same order of magnitude as the undisturbed horizontal speed (Jenkins *et al.*, 1981).

Subsequent theoretical studies have confirmed that this vortex arises from the elliptical shape of the island. The mechanism is essentially the same as vortex generation by a 'lifting body' such as an aircraft wing. However, it is surprising that with the 'stalled/separated' flow and an ellipticity of 1:1.5, a powerful vortex results.

In 1980 an experiment was mounted in the Sirhowy Valley, South Wales. This is one of a series of valleys with axes lying approximately north–south and together they form a reasonable approximation to a two-dimensional system which is much more amenable to theoretical analysis. As with Ailsa Craig an array of anemographs was used to record flow across the valley while Cardington turbulence probes (Readings and Butler, 1972) monitored turbulence levels from the tops of two masts and from the tethering cable of a kite balloon (see Figs 2, 3, 4 and 5). This pilot experiment revealed several interesting features, notably much higher levels of turbulence than expected. These and other points were studied further last year when a group from the Branch returned to the site with new equipment better suited for use in high turbulence levels. Of particular interest are a sonic anemometer, some hot-film instruments and the new 'mean-value' probe previously mentioned. The weather proved quite favourable with strong westerly flows for much of the time. Thus it should prove possible to identify the main characteristics of the flow from the data set, including the high turbulence levels and the 'separation bubble' which occurs in the lee of the windward ridge. The latter was in fact shown up at times during the experiment by the use of small zero-lift balloons. Tracer experiments were carried out at the same time and will be used to check the analysis of airflow.

Further experiments are planned on a hill in North Uist in the Outer Hebrides which meets all the criteria needed to carry out a definitive experiment, namely it is isolated, easily accessible, of uniform shape and of uniform roughness, being free of hedges, trees and the like. Data obtained from this site, using equipment now becoming available, should be of sufficiently high quality to test the various theories properly, particularly those involving turbulence parameters because, for the first time, changes in turbulence structure should be mainly determined by the general shape of the hill and not reflect local changes in roughness.

Theoretical work

At present there is a sound theoretical basis for the study of laminar flow over obstacles, though numerical investigations of separated flows have only recently been undertaken (Mason and Sykes, 1979a; Sykes, 1978). However, if accurate predictions of wind speed near the surface are to be made, then

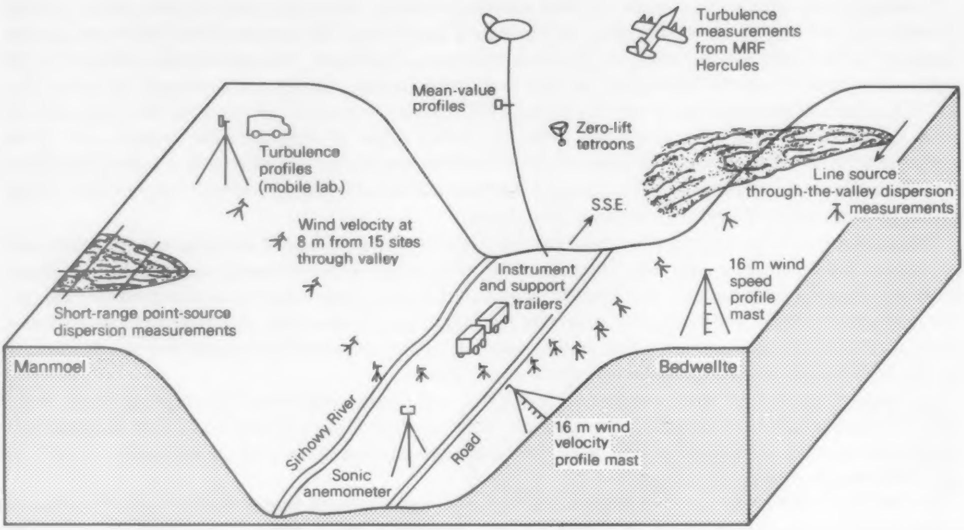


Figure 2. The Sirhowy Valley experiment, 1981

the fact that the atmosphere is turbulent must be taken into account and a convincing model has yet to be formulated.

To compare with the Brent Knoll experiment, Mason and Sykes (1979b) extended Jackson and Hunt's linear analytic theory of flow over gentle topography to three dimensions and it was surprising how well this model predicted many of the features observed experimentally, given the relative steepness of the hill's slopes. Subsequently, however, Sykes (1980) developed a higher order asymptotic theory for flow over a shallow ridge and showed that even a simple representation of the flow (i.e. an inviscid potential flow) is adequate as far as perturbations in mean velocity are concerned, so they are not a sensitive test of theoretical models. Thus, for the case of gentle topography, measurements of more sensitive quantities such as the Reynolds stresses are needed to test the validity of theoretical models adequately; hence the planned experiment in North Uist. Interest in these Reynolds stresses is not academic; they are vital for determining pollution dispersal and wind loading and their details are critical in determining the net momentum transfer between the boundary layer and the free atmosphere above.

In steeper topography, when flow separations may occur, even the mean flows are very poorly understood. The main features revealed by the Ailsa Craig experiment have been qualitatively explained by the application of a three-dimensional laminar-flow model but quantitative work awaits the development of a fully turbulent model. However, the two-dimensional numerical model described earlier has been applied to the site of the field experiment in South Wales. Initial results have confirmed the extent of the surface separation region and it is hoped that the extended data acquired in 1981 will provide further insights into the use of the model.

In turbulent flow over hills, the divergence in the Reynolds stress only dominates the pressure gradient and advective effects in the thin equilibrium region near the surface, so to model such flow successfully a high resolution normal (and close to) the surface is needed. Accordingly a 'terrain-following' (as opposed to the original 'Cartesian mesh') co-ordinate numerical model has now been set up. In this, the

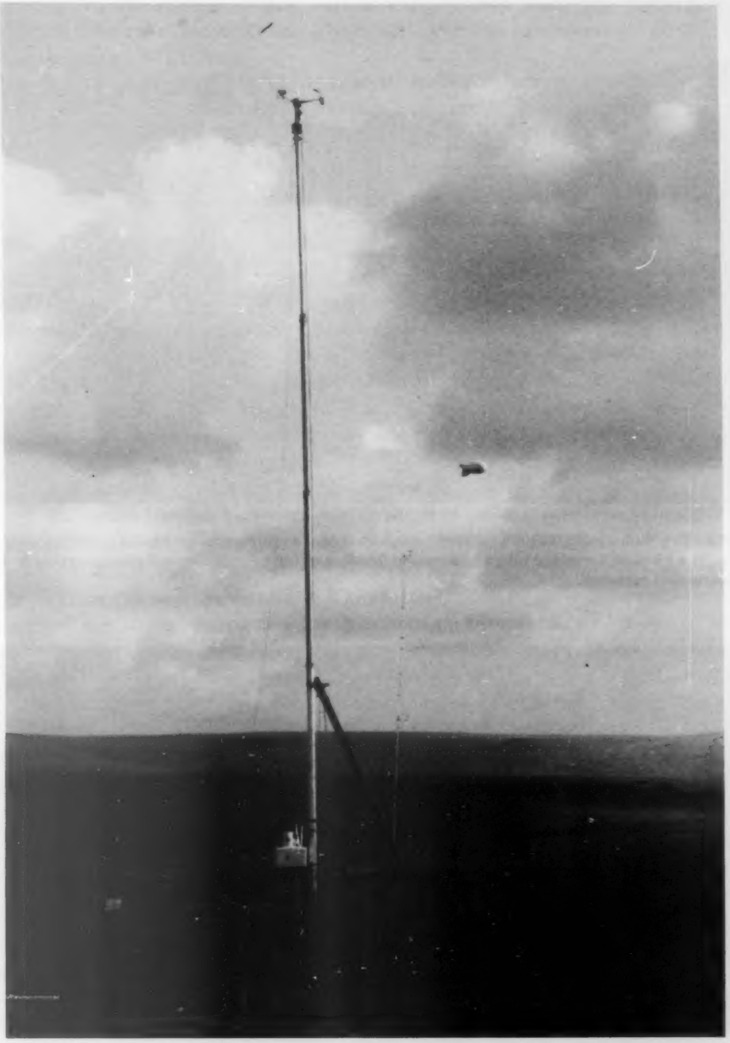


Figure 3. The Sirhowy Valley experiment. Measurements of turbulence levels, requiring fast-response sensors and high-speed data logging, were made on hill tops and in the valley through the use of a mobile laboratory. Seen here is turbulence instrumentation atop a 16-metre mast on one of the hills; a further 16-metre wind profile mast is visible behind, as well as the tethered balloon flown above the valley.

Figure 4. The Sirhowy Valley experiment. The winds which blew in the optimum direction for gathering data on cross-valley flow also brought with them torrential rain which caused flooding of the balloon site and made working conditions difficult around the instrument caravans.

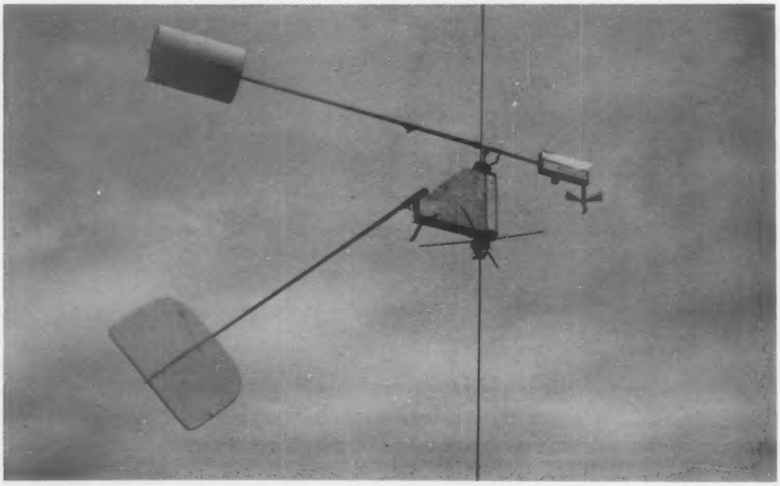


Figure 5. Development of boundary-layer instrumentation. Measurements of wind speed and direction, temperature, humidity and pressure are digitally telemetered every 3 seconds from this prototye mean-value probe supported on a tethered balloon cable. The probe, as well as being used to provide profile data on field experiments, acts as a test bed for some sensors which are to be incorporated into a second-generation Cardington turbulence probe now under design.

surface (as opposed to an absolute height) acts as the reference level, thus helping to ensure that resolution is highest where it is most needed. The model, with this extension, has already been used to study flow over the South Wales valley.

Although the three-dimensional form of the analytic model of Jackson and Hunt and the Branch's own two-dimensional numerical model have provided some insight into flow over surface features, the next big step must be the application of a numerical three-dimensional large-eddy model capable of modelling turbulent flow properly. As already mentioned, the development of such a model is in hand.

Atmospheric dispersion

Introduction

The Office's advice is often sought on how material released into the atmosphere will be dispersed and transported. Typical examples are releases of sulphur compounds, radio-nuclides, toxic materials, inflammable vapours and heavy gases. Some will be accidental and of short duration, others will be continuous over long periods, and each poses different problems. Routine enquiries are generally handled by the Special Investigations Branch, leaving the Boundary Layer Branch free to concentrate on research aimed at furthering our understanding of dispersion and the mechanisms which control it, or to deal with major problems which raise new or non-routine issues.

Dispersion and subsequent deposition processes are important in determining concentrations both in the atmosphere and on the ground. However, a wide range of scales is involved, ranging from a few tens of metres to global distances. Thus it is convenient to divide the ranges of interest into four main categories:

Short range — from the source out to a few kilometres.
Medium range or mesoscale — tens to a few hundreds of kilometres.
Long range — several hundreds of kilometres and more.
Global — this covers interhemispheric and tropospheric–stratospheric exchanges and is not dealt with in this article.

Short-range dispersion

In this range, details of the actual release (i.e. source height, duration, etc.) and the structure of the atmospheric boundary layer all have to be considered. Turbulence plays a dominant role and ultimately its variability limits the accuracy with which concentrations and dosages can be predicted — the problem becoming more acute the shorter the period being considered. This makes the use of sophisticated models difficult to justify in many instances. The Branch has recently carried out a preliminary study of this problem, seeking to relate the sensitivity of a simple Gaussian model to uncertainties in the basic meteorological parameters. Surprisingly, this showed that surface concentrations were not markedly affected by variations in vertical mixing, being much more dependent on variations in the horizontal wind components, though any mean inclination of the flow to the ground was also important. This makes the use of the concept of an eddy diffusivity to represent turbulence processes seem quite reasonable in many instances because, although the consequent errors may be substantial, they are generally acceptable compared with the specifications of other parameters affecting plume dispersal.

The resulting diffusion equation has been solved analytically only for rather idealized conditions, so for more realistic studies numerical techniques have to be used. An alternative approach which the Branch has used for many years (Smith, 1968; Hall, 1975), is the 'random walk' model in which the trajectories of particular elements of fluid (called particles) are calculated through the step-wise

application of equations which simulate the effect of real eddies. In the most recent version developed in the Branch (Ley, 1982), these equations, whilst correlating the motion of the particle with its earlier motion, introduce a new randomly selected impulse at each time-step characteristic of its position which ensures that, in a statistical sense, mass, momentum, energy and shearing stress are conserved. This model has already been used by the Branch to simulate dispersion in neutral conditions; the results show good agreement with experimental data, analytic solutions and established theory. A variant of this model has been developed for use by the Agricultural Meteorology Branch to study crop-spraying under a variety of conditions. At present it is being extended to cover stable conditions and ultimately it is hoped to apply it to unstable conditions and to other cases of practical interest. The technique is also to be used to study the relative diffusion of two or more particles in order to examine the development of short-release clouds and the likely variations of concentrations within a continuous plume. This work has relevance to the detection of odours, chemical defence problems, inflammable vapours and air chemistry.

Two basic processes control the vertical spread of material in the atmosphere, namely mechanical mixing and buoyant mixing. The former is directly related to the wind speed and the latter to temperature differences which lead to the vertical transfer of heat energy either from the surface to the air (a positive heat flux: unstable conditions) or from the air to the surface (a negative heat flux: stable conditions). A positive heat flux encourages vertical mixing while a negative one inhibits it. Normally, however, the heat flux cannot be measured directly on a routine basis so it has to be determined indirectly. A comprehensive set of data on the surface energy balance recorded at Cardington, Bedfordshire, covering a period of one year, is being analysed to see how the heat flux can best be estimated from routine meteorological observations. The first stage of this work, namely developing a method for estimating the reduction of solar radiation by varying amounts of different types of cloud, has already been completed. The results of this work will be used to improve a scheme for assessing the stability of the atmosphere from simple parameters such as wind speed, cloud cover, etc. This scheme, which is widely used, was originally developed by Dr F. Pasquill and has since been extended and put on a firmer theoretical basis (Smith, 1979).

In parallel with this work, precision instrumentation whose output is logged has been established at Porton, Wiltshire, in order to assess various alternative schemes that have been proposed for estimating Pasquill stability. This involves the measurement of variables such as temperature gradient, radiation, and fluctuations in wind direction. Data are also being recorded at a site in Scotland, at Torness, where the Branch has established similar instrumentation at the instigation of the South of Scotland Electricity Board. A nuclear power-station is being constructed at Torness and the meteorological data will be used to determine the dispersion climatology of the area required by the Board for risk assessment analyses.

Another topic attracting great interest at present is the consequences of releasing a large cloud of heavy vapour into the atmosphere. The Health and Safety Inspectorate are sponsoring some field trials involving several controlled releases and the Branch was asked to conduct an experimental study aimed at determining the feasibility of using upwind direction measurements to optimize the moment of release for the gas cloud so that it travels well within the downwind network of sampling monitors. This work, which is now complete, has clearly demonstrated the potential of the technique in slightly unstable conditions when the wind speed is above 3 metres per second.

Medium-range dispersion

Dispersion at short ranges depends mainly on turbulent diffusion but, as the distance of travel increases, the pattern of concentration at a given location becomes increasingly dependent on variations in the general wind flow associated with synoptic developments, on mesoscale circulations (e.g. lee

depressions and sea-breezes) and on the presence of topographic features, as well as on the time-evolution of the boundary layer. Deposition, chemical reactions and the nature of the source must also be considered. It is a complex area to study as few approximations are viable. The results find application in chemical warfare, the spread of viruses and major releases of radio-nuclides.

Here the Branch's work on flow round hills has found application in two areas. The first is in predicting the spread of foot-and-mouth virus by developing a technique which allows for the presence of hills, ridges, etc. This appears to improve significantly the Office's ability to forecast realistically areas at risk (Blackall and Gloster, 1981). It was successfully used by the Agricultural Meteorology Branch to predict the possible spread of the virus during the outbreak in Brittany, Jersey and the Isle of Wight in the spring of 1981. Several countries have expressed an interest in the technique.

The second area of application is to the problem of plume dispersal in laminar flow round an isolated hill. Two findings of particular interest are the large changes in surface concentration which can arise through plume impact and the increase in plume dispersion caused by flow distortion (Mason and Sykes, 1981). In support of this work some tracer studies were carried out during the 1981 Sirhowy Valley experiment. It is hoped that these data will prove suitable for checking the findings of the theoretical models.

Long-range dispersion

At these ranges the distribution of pollutants is basically independent of the characteristics of the source (apart from the duration of release). Trajectories are frequently curved, and elements of the plume may experience several diurnal cycles of the boundary layer. Concentration profiles tend to be rather uniform throughout the depth of the boundary layer and the losses of pollutant by various processes, such as wet and dry deposition, are significant. The lateral width of the 'plume' depends on synoptic developments as well as the period of release (or sampling).

There is considerable interest in this topic, both in Europe and North America, arising mainly from concern over possible damage to the natural environment caused by 'acid rain'. Large areas in Scandinavia and Canada are particularly sensitive owing to the nature of their soils and rocks. The acidity of rain is often quite high (pH = 3 to 4) and a contributory factor to this acidity is the uptake of pollution emitted into the air from fossil-fuelled industrial installations sometimes many hundreds or thousands of kilometres upstream. Unless effectively buffered in the soil there is some evidence that this acid can have lasting consequences for fish populations and other biosystems.

The Branch has played an active role in two major international projects concerned with this problem. The first was under the auspices of the Organization for European Co-operation and Development (OECD) and started in 1971. The second, under the United Nations Environmental Program, was started in 1978. Recently a very simple model has been developed within the Branch to simulate the emission–transport–conversion–deposition cycle of industrial pollutants in Europe. This model produces reasonably realistic estimates of dry and wet deposition in good accord with measured values. It requires very little computer time so it can be used to explore the effects of changing basic parameters such as the rate at which sulphur dioxide is converted to sulphate. Furthermore it can serve as a yardstick by which to judge more complex models, to see whether extra sophistication really produces worthwhile improvements in deposition estimates. The concept of wet and dry synoptic regions is being added to the model in order to judge whether to develop a complex stochastic model capable of simulating the variability of rainfall in space and time. This development is coupled with the use of trajectory analyses, together with radar data from the Meteorological Office Radar Research Laboratories at Malvern, to study the probability of rain occurring at specified points along a trajectory. This relates directly to a theoretical study which introduced a stochastic element, intended to represent the patchy nature of rain,

into a numerical model for predicting the long-range transport of material (Smith, 1981). Current models employ spatially and temporally smoothed rainfall fields and tend to underestimate the long-range transport of pollutants by removing them too quickly.

In support of this work the Branch is also active on the experimental side, notably in a joint experimental study of the long-range transport of pollutants being carried out in collaboration with the Central Electricity Research Laboratories, Leatherhead, as well as the Cloud Physics Branch. This uses chemical samplers installed in the instrumented Hercules aircraft from the Meteorological Research Flight to track the advection of pollutants from a particular source for long distances across the North Sea. The plume from a power-station in South Yorkshire is 'labelled' with two tracer gases so that it can be uniquely identified in both space and time and hence the same portion of plume tracked for long distances. Eleven flights have already taken place including one 'two-day' study when the same plume was tracked across the North Sea for two successive days (see Fig. 6). Plumes have been detected at distances as far as 700 km from the source.

The Central Electricity Research Laboratories are using data from these flights to study chemical transformations in the atmosphere, while the Branch is particularly interested in the travel and structure of plumes and the loss of pollutants from the boundary layer. Analysis has already advanced sufficiently for several interesting points to emerge, notably the generally fragmented nature of the plumes, possibly reflecting the presence of mesoscale features not detected by standard meteorological observations. One such system was found over the North Sea just downwind of the Yorkshire Moors.

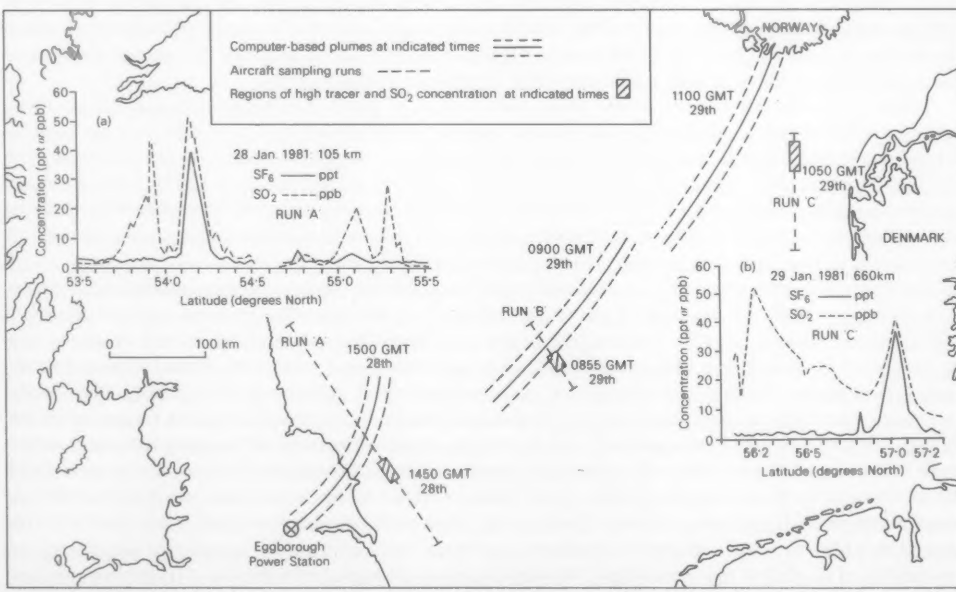


Figure 6. Plume study: two-day experiment, 28–29 January 1981. Inset diagrams (a) and (b): Variation of concentration of sulphur dioxide and tracer with latitude along aircraft sampling runs at 105 and 660 km from Eggborough.

In a similar vein, the Branch participated in a joint study, together with other parts of the Meteorological Office, of the plume from the main explosion of the Mount St Helens volcano, Washington. A trajectory model (basically a modified form of the operational one used by the Central Forecasting Office) was used to study the movement of the plume; it showed that while most of the plume reaching the eastern Atlantic was at low latitudes, fragments moved on a more northerly track towards the United Kingdom and Scandinavia, a prediction confirmed by aircraft observations over The Wash and over southern Scandinavia. Amongst other things, work of this nature has great relevance to the long-range dispersion of radio-nuclides from nuclear installations, whether one is considering small continuous releases (as covered by Article 37 of the Euratom Treaty) or large releases in accidents.

Conclusion

As this article has tried to show, the work of the Boundary Layer Branch covers a wide range of subjects and finds application in many and diverse fields. Many of the enquiries received in recent years cannot be answered in terms of simple idealized pictures of boundary-layer behaviour but require a deep knowledge of the basic turbulence characteristics, physics and meteorology. The Branch cannot study each subject in detail but, by concentrating on a few selected topics chosen because of their immediate relevance, it aims to make substantial progress with these topics, while maintaining a broad level of competence that can be applied to boundary-layer problems of any type, whenever they may arise.

References

Barnes, G., Emmett, G. D., Brummer, B., LeMone, M. A. and Nicholls, S. 1980 Structure of a fair weather boundary layer based on results of several measurement strategies. *Mon Weather Rev*, **108**, 349–364.

Blackall, R. M. and Gloster, J. 1981 Forecasting the airborne spread of foot and mouth disease. *Weather*, **36**, 162–167.

Carson, D. J. 1973 The development of a dry inversion-capped convectively unstable boundary layer. *Q J R Meteorol Soc*, **99**, 450–467.

Caughey, S. J., Crease, B. A., Cole, R. S., Asimakopoulos, D. N. and Moulsley, T. J. 1980 Quantitative interpretation of acoustic echoes from the planetary boundary layer. *Radio Electron Eng*, **50**, 598–610.

Caughey, S. J. and Rayment, R. 1974 High-frequency temperature fluctuations in the atmospheric boundary layer. *Boundary Layer Meteorol, Dordrecht*, **5**, 489–503.

Caughey, S. J. and Readings, C. J. 1975 An observation of waves and turbulence in the Earth's boundary layer. *Boundary Layer Meteorol, Dordrecht*, **9**, 279–296.

Cole, R. S., Asimakopoulos, D. N., Moulsley, T. J., Caughey, S. J. and Crease, B. A. 1980 Some aspects of the construction and use of atmospheric acoustic sounders. *Radio Electron Eng*, **50**, 585–597.

Davis, P. A. and Peltier, W. R. 1980 Some characteristics of the Kelvin–Helmholtz and resonant over-reflection modes of shear flow instability and their interaction through vortex pairing. *J Atmos Sci*, **36**, 2394–2412.

Hall, C. D. 1975 The simulation of particle motion in the atmosphere by a numerical random-walk model. *Q J R Meteorol Soc*, **101**, 235–244.

Jenkins, G. J., Mason, P. J., Moores, W. H. and Sykes, R. I. 1981 Measurements of the flow structure around Ailsa Craig, a steep, three-dimensional isolated hill. *Q J R Meteorol Soc*, **107**, 833–851.

Kaimal, J. C., Wyngaard, J. C., Haugen, D. A., Coté, O. R., Izumi, Y., Caughey, S. J. and Readings, C. J. 1976 Turbulence structure in the convective boundary layer. *J Atmos Sci*, **33**, 2152–2169.

Ley, Anne J. 1982 A random walk simulation of two-dimensional turbulent diffusion in the neutral surface layer. *Atmos Environ*, **16**, 2799–2808.

Mason, P. J. and Sykes, R. I. 1979a Separation effects in the Ekman layer flow over ridges. *Q J R Meteorol Soc*, **105**, 129–146.

1979b Flow over an isolated hill of moderate slope. *Q J R Meteorol Soc*, **105**, 383–395.

1980 A two-dimensional numerical study of horizontal roll vortices in the neutral atmospheric boundary layer. *Q J R Meteorol Soc*, **106**, 351–366.

1981 On the influence of topography on plume dispersal. *Boundary Layer Meteorol, Dordrecht* **21**, 137-157.

Moores, W. H., Caughey, S. J., Readings, C. J., Milford, J. R., Mansfield, D. A., Abdulla, S., Guymer, T. H. and Johnston, W. B. 1979 Measurements of boundary layer structure and development over SE England using aircraft and tethered balloon instrumentation. *Q J R Meteorol Soc*, **105**, 397–421.

Nicholls, S. 1978 Measurements of turbulence by an instrumented aircraft in a convective atmospheric boundary layer over the sea. *Q J R Meteorol Soc*, **104**, 653–676.

Nicholls, S. and LeMone, M. A. 1980 The fair weather boundary layer in GATE: the relationship of subcloud fluxes and structure to the distribution and enhancement of cumulus clouds. *J Atmos Sci*, **37**, 2051–2067.

Nicholls, S. and Readings, C. J. 1979 Aircraft observations of the structure of the lower boundary layer over the sea. *Q J R Meteorol Soc*, **105**, 785–802.

1981 Spectral characteristics of surface layer turbulence over the sea. *Q J R Meteorol Soc*, **107**, 591–614.

Palmer, S. G., Caughey, S. J., and Whyte, K. W. 1979 An observational study of entrainment convection using balloon-borne turbulence probes and high-power Doppler radar. *Boundary Layer Meteorol, Dordrecht*, **16**, 261–278.

Rayment, R. 1973 An observational study of the vertical profile of the high-frequency fluctuations of the wind in the atmospheric boundary layer. *Boundary Layer Meteorol. Dordrecht*, **3**, 284–300.

Rayment, R. and Readings, C. J. 1974 A case study of the structure and energetics of an inversion. *Q J R Meteorol Soc*, **100**, 221–233.

Readings, C. J. and Butler, H. E. 1972 The measurement of atmospheric turbulence from a captive balloon. *Meteorol Mag*, **101**, 286–298.

Smith, F. B. 1968 Conditioned particle motion in a homogeneous turbulent field. *Atmos Environ*, **2**, 491–508.

1979 The relation between Pasquill stability *P* and Kazanski–Monin stability μ (in neutral and unstable conditions). *Atmos Environ*, **13**, 879–881.

1981 The significance of wet and dry synoptic regions on long-range transport of pollution and its deposition. *Atmos Environ*, **15**, 863–873.

Sykes, R. I. 1978 Stratification effects in boundary-layer flow over hills. *Proc R Soc. London*, A **361**, 225–243.

1980 An asymptotic theory of incompressible turbulent boundary-layer flow over a small hump. *J Fluid Mech*, **101**, 647–670.

Thompson, N., Webber, K. L., and Norris, B. P. 1980 Eddy-fluxes and spectra in the GATE sub-cloud layer. *Q J R Meteorol Soc*, **106**, 277–292.

551.577.51(416)

Exceptional orographic rainfall in the Mountains of Mourne

By S. J. Caughey
(Meteorological Office, Belfast/Aldergrove Airport)

and S. J. G. Partington
(Meteorological Office, Belfast)

Summary

Between 0100 GMT on 27 December and 0900 GMT on 29 December 1978, about 245 mm of rain fell in the central area of the Mountains of Mourne. The synoptic context in which this occurred is examined and it appears that orographic enhancement (by up to 10 mm h^{-1}) of background moderate to heavy rainfall was largely responsible for this exceptional event. The enhancement was associated with a deep, very moist, low-level jet with a core speed of about 25 m s^{-1}, at about the 850 mb level, in a slow-moving synoptic situation. Evidence is also presented which indicates that the enhancement was abnormally high owing to the release of potential instability in the vicinity of the hills.

1. Introduction

The enhancement of rainfall through orographic effects has received recent attention in the literature (Bader and Roach 1977, Browning 1980, and Hill *et al.* 1981). In warm sectors of depressions and in the vicinity of surface fronts, rainfall is frequently found to be much heavier over hills than over adjacent lower ground. Bergeron (1965) first proposed a possible mechanism for this phenomenon. He suggested that raindrops falling from higher-level cloud could wash out sufficient numbers of small droplets in an orographically generated 'cap' cloud to significantly increase local rainfall rates. The largest increases (or enhancements) would be expected when the pre-existing rainfall rates were high and/or when strong, very moist low-level flow was present. In the latter case the liquid water removed from the cap cloud is rapidly replaced by fresh condensation through orographic uplift.

Hill *et al.* (1981) presented eight detailed studies of orographic rain over the 'Glamorgan Hills' (Blaenau Morgannwg) of South Wales, using radar and a network of autographic gauges. These results indicated that most (about 80%) of the enhancement occurred in the lowest 1.5 km above the hills and was more marked at the first range of hills encountered. Thus enhancements over the Brecon Beacons were normally substantially less than those over the Glamorgan Hills. Rain-shadow effects over downstream low ground may also be particularly well marked in enhancement situations (Pedgley 1970).

This paper discusses an example of exceptionally heavy orographic rainfall that occurred between 27 and 29 December 1978 in the Mountains of Mourne, which lie in the south-east of Northern Ireland. Rainfall rates reached 14 mm h^{-1} in the central area of the hills whilst at a nearby coastal site the maximum rainfall rate was about 6 mm h^{-1}. Remarkable rainfall totals accumulated because the rainfall continued for a considerable time in a slow-moving synoptic situation.

In the vicinity of the hills the consequences of the heavy rainfall were dramatic. Thousands of acres of farmland were flooded and many roads became impassable. Sections of the Castlewellan–Banbridge road were washed away and some areas flooded to a depth of about eight feet. The bridge at Tullynisky on the main Banbridge road was damaged by floodwater on 27 December and later was washed away completely.

2. Background to the investigation

The area of particular interest in this study is that bounded by the dashed lines in Fig. 1(a), i.e., the Mountains of Mourne in the south-east corner of Northern Ireland. Also indicated is the position of the Long Kesh radiosonde station which lies about 35 km to the north. During the event to be described the low-level wind direction was east-south-easterly (about 100°) and so the radiosonde station did not provide information on upstream characteristics. Nevertheless, it was not directly downstream from the hills and the observations are taken as giving some guidance to variations of the 600 m wind speed with time close to the hills. Fig. 1(b) illustrates the main features of the topography of the area and shows the

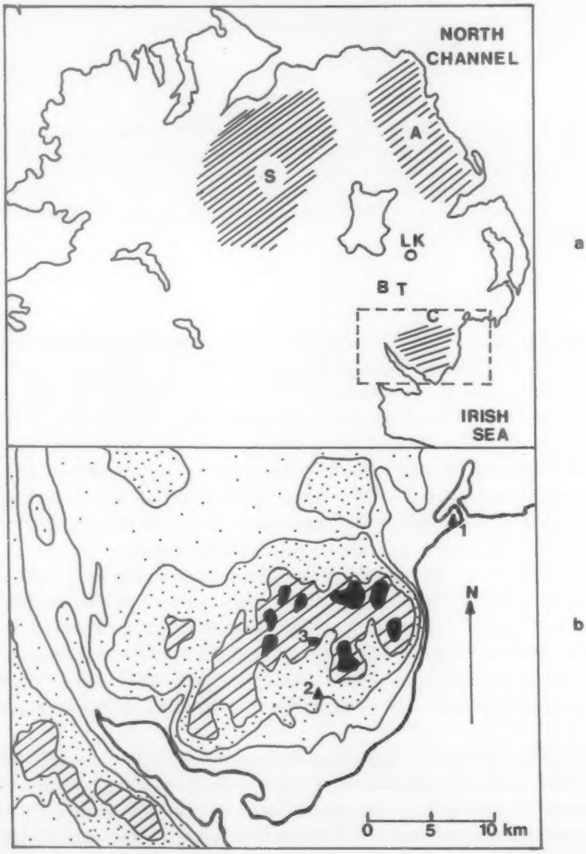


Figure 1. Northern Ireland, showing the area investigated. (a) The experimental area (bounded by dashed lines) and Long Kesh radiosonde station (LK) in relation to Northern Ireland. Also shown are the locations of some places referred to in the text: B — Banbridge, C — Castlewellan, T — Tullynisky, A — Hills of Antrim, S — Sperrin Mountains. Hatched areas indicate high ground. (b) Topographical characteristics of the experimental area (Mountains of Mourne and adjacent regions). Unstippled areas range from 0 to 60m above mean sea level, light stippling from 60 to 120m, heavy stippling from 120 to 300m, hatched from 300 to 600m, and the dark areas represent land above 600m. The principal rain-gauge sites are also shown, ie. coastal gauge (site 1) and hill gauges (sites 2 and 3).

positions of the principal rain-gauges employed in the study. These are the coastal autographic gauge (site 1, height 9 m), Silent Valley autographic gauge (site 2, height 129 m) and the Miner's Hole magnetic tape event recorder (site 3, height 311 m). It can be seen from Fig. 1(b) that with a wind direction of 100° the coastal gauge is not upstream of the hills, but about 12 km to the north-east. Smaller-scale features of the rainfall field cannot therefore be expected to appear in the rain-gauge traces for the hills and the coast. This aspect is considered further in section 5.

It is useful to examine the variation of annual rainfall with height in the Mountains of Mourne area and how this compares with the results for the Glamorgan Hills of South Wales as presented by Hill *et al.* (1981). The data selected for the Mountains of Mourne are taken from a carefully quality-controlled set of autographic gauges that cover the height range of interest in this study. Higher-level gauges are available but there is doubt as to their accuracy owing to infrequent reading (mainly monthly) and exposure. No attempt has been made to average the height of topography in small areas upstream in the direction of the prevailing wind to obtain an 'effective' gauge height that reduces scatter (see Hill *et al.* 1981) in the height versus amount plot (see Fig. 2). Substantially more rainfall occurs near sea level in South Wales than in the south-east of Northern Ireland. However, the slopes of the two lines are similar

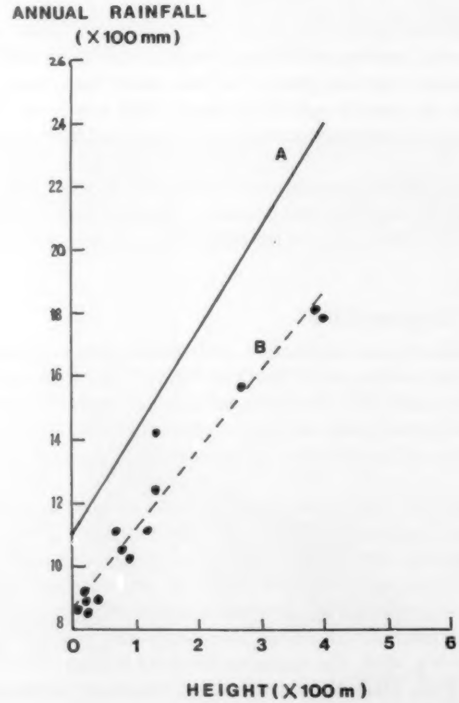


Figure 2. The variation of annual rainfall with height in the Mountains of Mourne (dots) using data from autographic gauges only. Line 'B' is a 'by-eye' fit to the points and line 'A' is a fit to the data for the Glamorgan Hills (see Hill *et al.* 1981).

and, eliminating the dependence of the slopes on the intercepts R_0 (i.e. the rainfall at or near sea level), give the following forms:

$$R_h = R_0\,(1 + 0.0029h) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \text{(1a)}$$
$$R_h = R_0\,(1 + 0.0030h) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \text{(1b)}$$

where equation (1a) applies to the Glamorgan Hills of South Wales and (1b) to the Mountains of Mourne (R_h is the annual rainfall at a height of h metres). In the former case R_0 is 1100 mm whilst in the latter it is about 860 mm. It is interesting that the height dependence is very similar in the two areas, which may imply that similar rainfall enhancement processes are responsible. In the Glamorgan Hills 75% of the total rainfall in the hills was associated with low-level winds (above the friction layer) from the south-west quadrant, whilst 60% of the total fell on the coasts in these situations.

The average annual rainfall on the highest ground is about 2500 mm (Hill *et al.* 1981). If F_h and F_0 represent the fractions of the total rainfall associated with winds from the south-west quadrant, in the hills (at height h) and on the coast respectively, then the average enhancement is given by:

$$\bar{E}_h = \frac{F_h R_h}{F_0 R_0} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

which for the Glamorgan Hills is about 3.

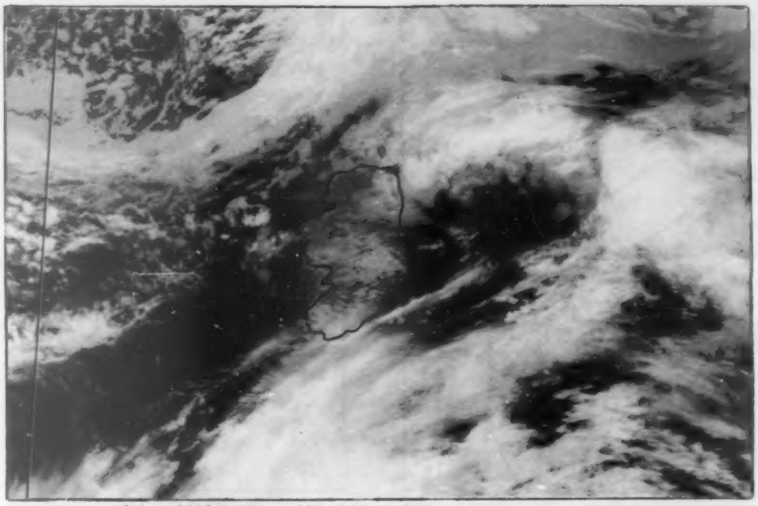
In the Mountains of Mourne onshore winds arise mainly from the south-east quadrant and in this sector about 35% of the annual rainfall falls in the hills whilst the corresponding figure for coastal regions is about 30%. Since the annual rainfall is about 1800 mm in the higher parts of these hills equation (2) indicates that the average enhancement to be expected from the coast to a height of about 300 m is about 2.5.

It should be noted that equation (1b) may have some predictive value in that if R_0 is known for a particular rainfall event then the equation can be used to obtain an estimate of the likely rainfall in the hills (but not on higher ground downwind of the hills). This aspect is considered further in section 5.

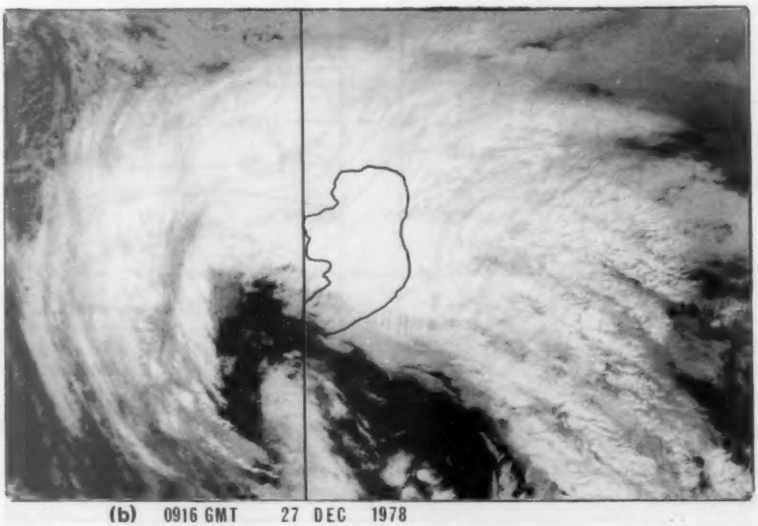
3. Synoptic situation 27/28 December 1978

The primary purpose of this article is to describe, and to offer some explanation for, the exceptionally heavy rainfall that affected the eastern part of Northern Ireland (essentially counties Antrim and Down) during the period 27–29 December 1978. The infra-red satellite images available highlight the synoptic development that occurred as a deepening depression approached the British Isles from the south-west. Figs 3(a) and (b) illustrate the movement of the cloud mass from the south across Ireland on 26 and 27 December.

With high pressure to the north and a developing anticyclone over Scandinavia the system became slow moving over south-west Ireland. Fig. 4 illustrates the movement of the associated rain areas over land (continued by extrapolation over adjacent sea areas). The rain moved quickly northwards across Northern Ireland and was associated with the arrival of very moist low-level air (see Fig. 4). For example, at Long Kesh the relative humidity at 900 m rose from 83% at 0001 GMT on the 27th to reach 96% by midday. By this time the rain had ceased over south-west Ireland following the passage of the warm occlusion indicated in Fig. 4(b). The clearance of cloud behind this front is well revealed by the satellite photograph (Fig. 3(b)). Over Northern Ireland, southern Scotland and northern England, however, the rain area persisted and became slow moving, gradually turning to sleet and snow as colder air moved southwards from northern Scotland. It would seem likely that advection of dry, cold air from the near continent into Scotland also took place as the flow became orientated in an approximate



(a) 0959 GMT 26 DEC 1978



(b) 0916 GMT 27 DEC 1978

Photographs by courtesy of University of Dundee

Figure 3. Infra-red satellite pictures taken at (a) 0959 GMT on 26 December 1978 and (b) 0916 GMT on 27 December 1978.

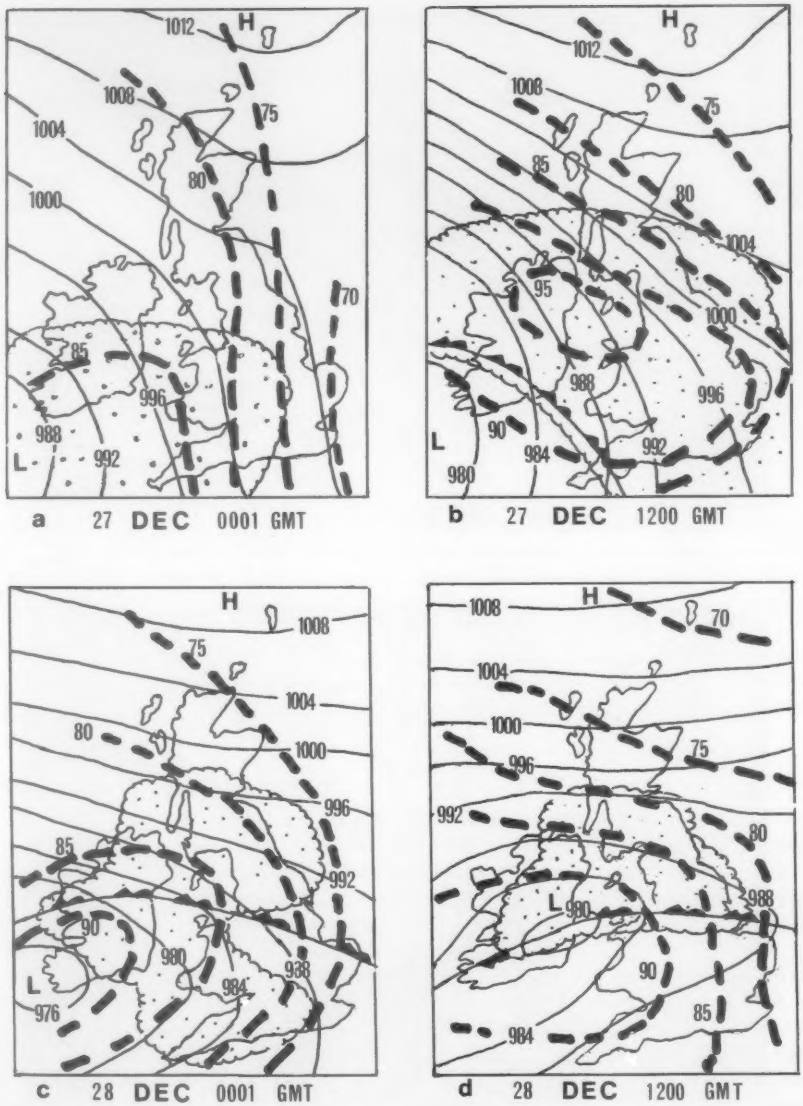


Figure 4. Surface synoptic charts for (a) 27 December 1978 at 0001 GMT, (b) 27 December 1978 at 1200 GMT, (c) 28 December 1978 at 0001 GMT, and (d) 28 December 1978 at 1200 GMT. The stippled area represents the extent of continuous rainfall from land observations and this has been arbitrarily extrapolated to include sea areas. Lines are isobars (mb) and dashed lines indicate relative humidity (%) at 900 m.

east–west direction (see Fig. 4(d)). Since the southwards advection of cold air was nearly at right angles to the flow it seems that ageostrophic motion may have been important, probably as a result of downstream acceleration of the flow (see Fig. 4(b)).

A cross-section of wet-bulb potential temperature (θ_w) extending from Valentia (in south-west Ireland) to Lerwick at 1200 GMT on 27 December is given in Fig. 5 and reveals an extensive baroclinic zone between Long Kesh and Lerwick. A second baroclinic zone occurs from about 600 mb to 480 mb between Long Kesh and Valentia. This is an upper cold front and suggests that the frontal structure corresponds to a warm occlusion, moving slowly northwards, being undercut by cold air at lower levels moving south. The position of the surface occlusion drawn in Fig. 4 is also given in Fig. 5. The locations of areas of potential instability (PI) are shown as stippled areas. These indicate low-level PI in the cold air over Lerwick and at higher levels in the vicinity of Long Kesh and Valentia.

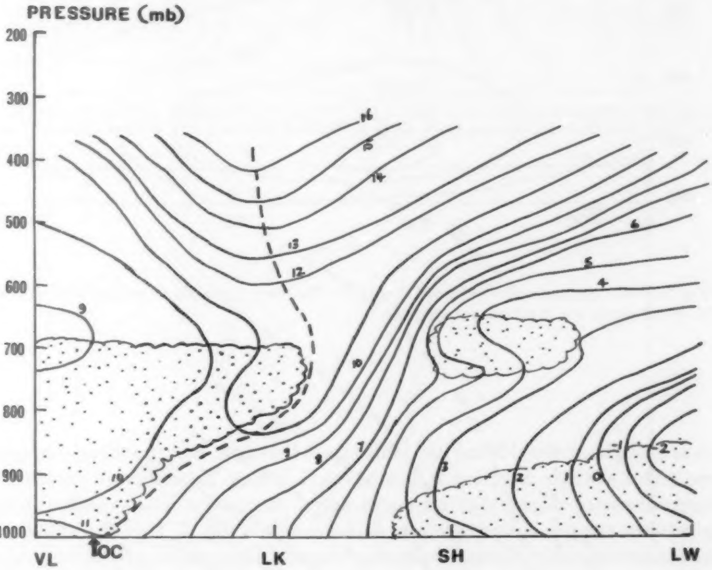


Figure 5. Cross-section of wet-bulb potential temperature (°C) from Valentia (VL), in south-west Ireland, to Lerwick (LW), with intermediate stations Long Kesh (LK) and Shanwell (SH) at 1200 GMT on 27 December 1978. Areas of possible potential instability are stippled. The dashed line represents the axis of maximum wet-bulb potential temperature. OC marks the position of the surface occlusion shown in Fig. 4.

Although the middle-level PI in the vicinity of Long Kesh appears marginal it is worth noting that Browning *et al.* (1973) reported cumulus-scale updraughts of up to 5 m s^{-1} in a rainband where radiosondes indicated that $\partial\theta_w/\partial z$ was only about -0.5 °C km^{-1}.

An important feature revealed by the cross-sectional analysis was the appearance of a strong low-level jet (J2 in Fig. 6). In this diagram the winds have been resolved along 120° (i.e. roughly parallel to the flow at 850 mb at 1200 GMT on the 27th). The low-level jet (core speed about 25 m s^{-1}) lies in a strongly baroclinic zone and has a south-easterly direction. The main tropospheric jet associated with the

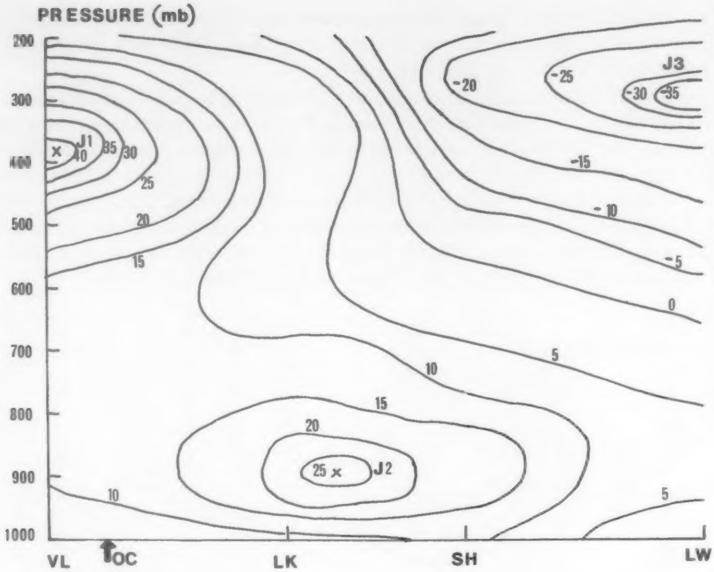


Figure 6. As Fig. 5 for the component of wind speed along 120°. The main tropospheric jets are labelled J1 and J3 and the low-level jet as J2. Wind speeds are in metres per second.

depression is at a height of 400–350 mb and is also from the south-east. A second tropospheric jet (at 300 mb), this time with a westerly direction, is located near Lerwick. The upper-air pattern therefore had the form of a highly distorted ridge lying from south-east to north-west across the British Isles. The spatial relationship between the jets discussed above is illustrated in Fig. 7. This also shows the 1000–500 mb thickness and sea-level pressure fields. The marked thermal ridge and cold trough (to the west of Ireland) decayed as the upper flow became more zonal by midday on the 28th.

Low-level jets associated with mid-latitude fronts have been discussed in the literature by Browning and Pardoe (1973). The airflow pattern shown in Fig. 6 is very similar to the results they presented for cold fronts. Similar features have been observed in association with occluded warm fronts (Kreitzberg 1968). Whilst the width of the jets may be only a few hundred kilometres they usually extend along-wind for thousands of kilometres and are therefore to be regarded as synoptic-scale features.

Fig. 8 shows the detailed airflow at 900 m across the British Isles at 1200 GMT on the 27th. The jet axis lies across Northern Ireland and then passes through North Wales to the west of England. Also shown is the position of the surface occlusion at this time and it is clear that the jet axis is ahead of the surface front and roughly parallel to it.

Browning and Pardoe (1973) suggested that low-level jets form in baroclinic zones and this is supported by the present study. Fig. 9 gives an isentropic analysis for 1200 GMT on 27 December and the dashed area shows the approximate location of the low-level jet (i.e. 900 m wind speed greater than

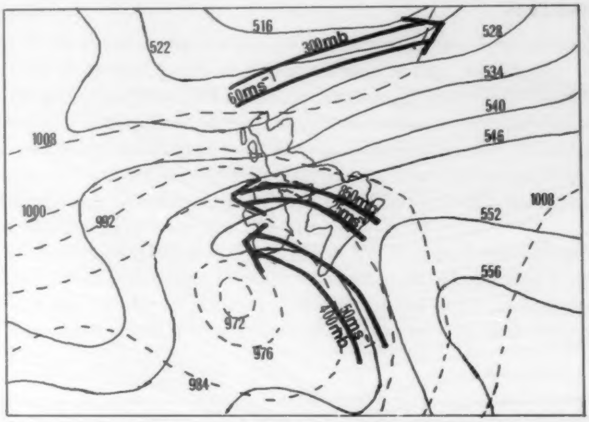


Figure 7. Surface pressure in millibars (dashed lines) and 1000-500 mb thickness fields in decageopotential metres (solid lines) for 1200 GMT on 27 December 1978. The positions and heights of the jet streams are also indicated, with the core speeds in metres per second.

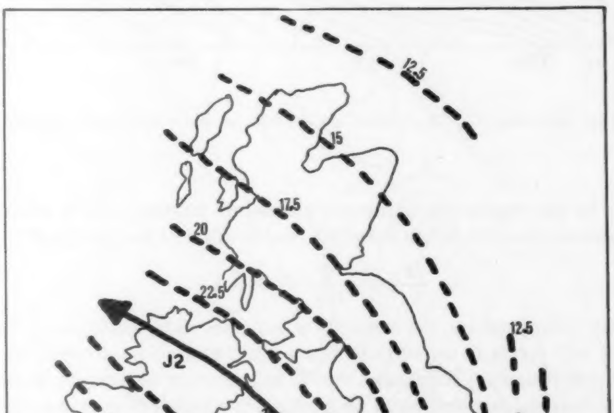


Figure 8. Airflow pattern at 900 m across the British Isles at 1200 GMT on 27 December 1978. The spatial extent and orientation of the low-level jet (J2) is indicated. Wind speeds are in metres per second.

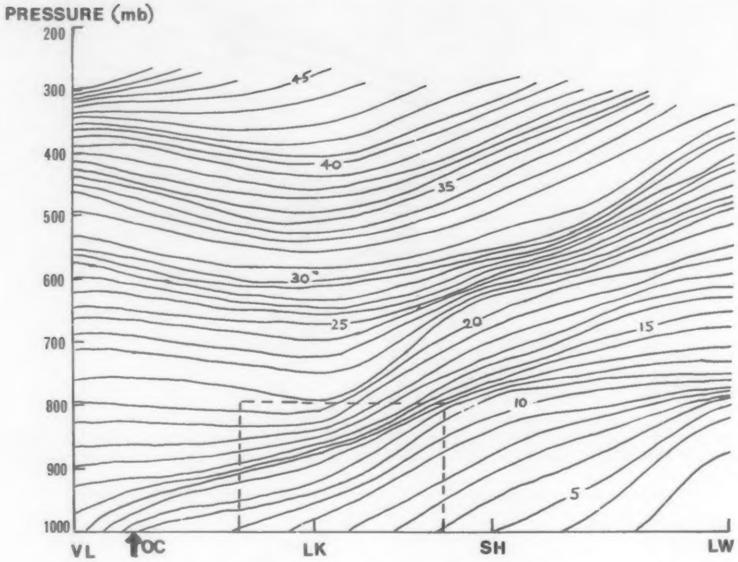


Figure 9. As Fig. 5 for isentropes (°C). The extent of the low-level jet (J2) is given approximately by the dashed lines.

about 20 m s^{-1}). In this region the isentropes are tightly packed, with a strong negative gradient northwards. The vector equation which describes the variation of the geostrophic wind with height is:

$$\frac{\partial \boldsymbol{V}_g}{\partial z} = -\frac{g}{fT_V}\nabla_p T_V \times \mathbf{k} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (3)$$

where T_V is the virtual temperature, the subscript p indicates differentiation on a surface of constant pressure and **k** is a unit vector in the vertical. For a south-easterly geostrophic wind and values of T_V decreasing to the north equation (3) indicates that $\boldsymbol{V}_g$ will decrease with height. Between 850 mb and 750 mb the expected decrease in this instance is about 8 m s^{-1} which is of the same order as that observed. Surface friction acts to reduce the wind speed near the ground and so the net effect is the appearance of an elevated wind maximum (or jet) near 850 mb.

The synoptic development previously outlined obviously resulted in widespread vertical air motion in the vicinity of the British Isles. An attempt to quantify this has been made using the cylindrical cross-section technique described by Pedder (1979). However, in view of the small number of radiosonde stations available and the sensitivity of the results to small errors in wind speed the conclusions can only be regarded as, at best, semi-quantitative. Nevertheless, they do throw some light on the intensity of the vertical motion occurring at the time. The radiosonde stations employed were Long Kesh, Aughton, Shanwell and Lerwick, and the positions of these stations were projected on a circle of about 160 km radius centred over south-west Scotland. Strong upwards motion was indicated at middle levels, i.e. the vertical velocity increased with height to reach about 8 cm s^{-1} at about 450 mb. Analysis of the 1200 GMT Long Kesh radiosonde ascent on 27 December shows that vertical motion of at least this order of magnitude is required to produce moderate rainfall.

4. Rainfall characteristics

The extreme nature of the event under discussion and evidence for a large orographic component in the rainfall totals are well illustrated by the distribution map in Fig. 10. For ease of compilation these totals refer to the period between 0900 GMT on 27 December and 0900 GMT on 29 December 1978 and so are not the maximum falls in the event. In fact, as cold air advected into the region from the north on the 28th and 29th the precipitation turned progressively to sleet and snow. Hence, the total equivalent rainfall in the higher parts (about 300 m) of the central area of the Mountains of Mourne between 0100 GMT on the 27th (when the rain commenced) and 2100 GMT on the 29th (when the snow finally ceased) is not known, but is likely to have exceeded 300 mm.

On the east coasts of counties Antrim and Down about 50–70 mm of rain fell (see Fig. 10) whereas in the hills of Antrim (300–600 m high) over 100 mm fell, and in the Mountains of Mourne, which were directly exposed to the winds off the sea, in excess of 200 mm fell in the central region. Downwind of these hilly areas the rain-shadow effect was remarkably prominent so that only 10 mm of rain were

Figure 10. Rainfall distribution over Northern Ireland for the period 0900 GMT on 27 December to 0900 GMT on 29 December 1978.

recorded in the western Lough Neagh basin and the lower Bann Valley. Further west, rainfall totals of about 25 mm were recorded in association with further orographic effects in the Sperrin Mountains. Pedgley (1970) presented rainfall cross-sections through the Snowdonia region of North Wales and obtained rain-shadow effects of a similar order of magnitude in some enhancement situations.

The accumulation of rainfall at the Silent Valley (site 2, Fig. 1(b)) is shown in log–log form in Fig. 11. This represents the maximum fall of rain in a particular period as a function of the duration of the period (see e.g. Jack 1981). The total period analysed was from 0100 GMT on 27 December to 0900 GMT on 29 December, i.e. a 56-hour period in which 245 mm of rain fell. Lines B and A give the once-in-100-years and once-in-1000-years falls as a function of rainfall duration based on 50 years' data from the Silent Valley — hence the once-in-1000-years predictions must be viewed with some caution. This event therefore became rarer than once in 100 years after about 15 hours duration and rarer than once in 1000 years after about 35 hours duration, which emphasizes that on short time-scales (1 to 5 hours) the rainfall totals were not unusually high. However, the cumulative effect of heavy rain maintained for a long time resulted in a two-day rainfall total for this site that is the highest since records began in 1930.

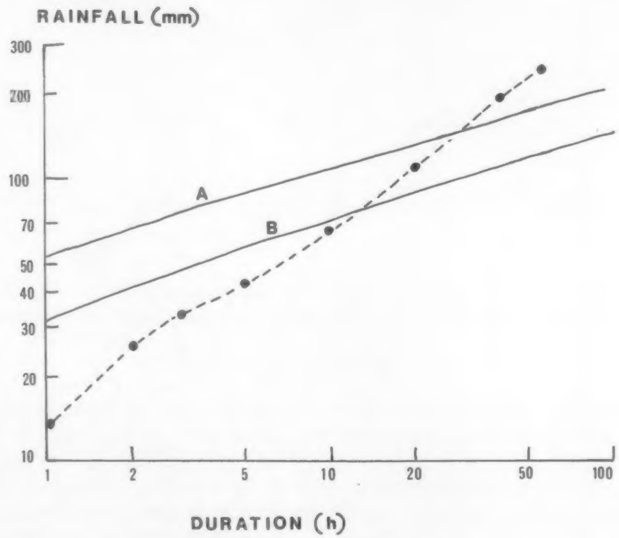


Figure 11. The maximum observed rainfall at the Silent Valley (site 2, Fig. 1(b)) as a function of the duration of the fall, from 0100 GMT on 27 December to 0900 on 29 December 1978.

5. Orographic enhancement

This section considers some aspects of orographic enhancement on 27 December, i.e. before falling temperatures turned the precipitation at the higher levels (and subsequently at low levels) to snow. The enhancement of rainfall (i.e. $P_h - P_0$, where P_h is the rainfall rate in the hills and P_0 the rate at the nearby coast), produced by orographic uplift, has been investigated theoretically by Bader and Roach (1977). In their model, small water droplets in an orographically produced cap cloud are washed out by raindrops

falling from a high-level cloud. Bader and Roach assumed the enhancement was associated with an initially saturated layer extending from the surface to 1.5 km and located entirely below the freezing level. The radar results reported by Hill *et al.* (1981) confirmed the appropriateness of these assumptions and provided convincing evidence for most of the enhancement occurring below 1.5 km above the hills (see e.g. Fig. 12 of their paper). Nevertheless, deficiencies in the model were implied by the observational data; in particular the dependence of the enhancement on wind speed was much greater than predicted whilst the dependence on P_0 was much less than predicted.

More recently Carruthers and Choularton (1983) have extended Bader and Roach's formulation to include the effect of stratification on the airflow over the hills and the influence of wind drift on the precipitation. They have also examined the dependence of the enhancement on hill height and the depth of the cap cloud. These calculations were restricted to hill lengths, L, (roughly speaking one-half the along-wind dimension of the hill or group of hills) $\leqslant$20 km and heights $\leqslant$1 km since the 'wash-out' mechanism is felt to be dominant in these cases. For longer hills there is sufficient time for coalescence in the cap cloud to produce raindrops, whilst over higher hills the character of pre-existing middle-level precipitation may be markedly altered. Carruthers and Choularton concluded that for long hills (L>7 km) the simple Bader and Roach model is adequate but that for short hills (L<2 km) it leads to underestimates of the enhancement. However, they could not model the high sensitivity of the enhancement to wind speed as reported by Hill *et al.* (1981) and speculated that this was a consequence of the structure of the low-level jets, normally associated with heavy orographic rainfall, deep moist jets (producing deep cap clouds), being associated with the highest wind speeds. Nevertheless, even for long hills (L = 20 km) of 600 m height and a 3 km deep cap cloud with a background rainfall rate P_0 = 2.5 mm h^{-1}, the maximum enhancement obtainable was only about 2.5 mm h^{-1}.

For the Mountains of Mourne L is about 8 km and so it is expected that the Bader and Roach model should provide reasonable results, except for the influence of hill slope.

In the model a slope of 1:100 was assumed, whereas in the Mountains of Mourne this varies between 1:30 and 1:10. Hill *et al.* (1981) have shown that an increase in slope from 1:100 to 1:40 could result in a 40% increase in orographic enhancement and so it is expected that the model results should be significantly less than those observed. The conditions required for strong orographic enhancement in hilly areas (summarized by Hill *et al.* 1981) were all fulfilled during this event, i.e. a nearly saturated strong low-level airflow (in the form of a low-level jet) was present and appreciable rainfall rates were recorded at nearby coastal sites. Fig. 6 shows that at 1200 GMT on the 27th wind speeds at around 900–850 mb reached 25 m s^{-1}. The average relative humidity in the lowest 1000 m, at this time, was about 93%.

The variation of total rainfall with height on 27 December is given in Fig. 12. On this day about 60 mm of rain fell on the coasts (in the vicinity of the hills) whilst at site 3 (about 311 m) more than twice this amount was recorded. The line labelled 'A' in Fig. 12 is the prediction for this event based on the behaviour of the annual rainfall with height, i.e.

$$R_h = 60(1 + 0.003h) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

and it is of interest to note that it provides a reasonable fit to the data. This suggests that most of the increase in rainfall with height in the Mountains of Mourne is due to orographic enhancement in similar situations to those described above.

The detailed variations of the low-level wind (heights less than 1.5 km) on the 27th are given in Fig. 13. Profile A (taken at 0001 GMT on 27 December) indicates wind speeds in the range 5–10 m s^{-1} and only a weak variation with height. By 0600 GMT on 27 December winds have increased at all levels and there is a suggestion of a low-level maximum at about 600–900 metres.

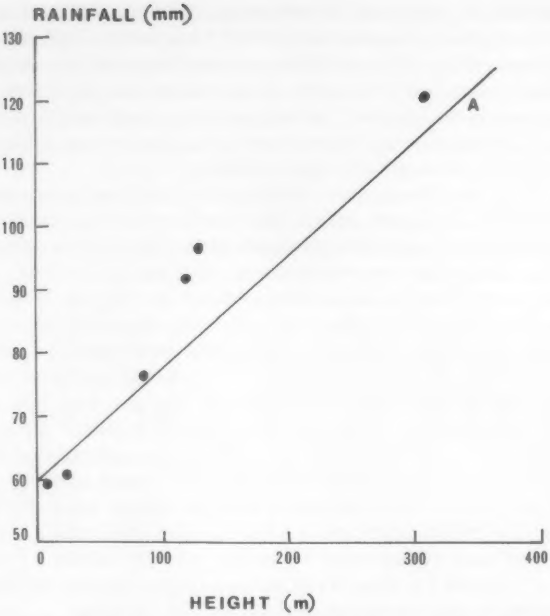


Figure 12. The variation with height of rainfall in the Mountains of Mourne from 0100 GMT on 27 December to 0001 GMT on 28 December 1978. Line 'A' represents the predicted variation based on the behaviour of the annual rainfall with height (Fig. 2).

The increase in wind speed continued in line with the synoptic developments discussed earlier so that by 1200 GMT speeds in the 600–900 m height range approach 25 m s^{-1}. By midnight the gradient had relaxed and wind speeds decreased (profile E).

Shown in Fig. 14 are hourly averages of the rainfall rate in the hills, P_h (site 3 in Fig. 1(b)) and at the coast, P_0 (site 1 in Fig. 1 (b)). Initially, with fairly moderate wind speeds, the enhancement, $P_h - P_0$, is small, but increases with time as a consequence of both increasing P_0 and wind speed. Smaller-scale features (i.e. 1 to 2 h duration) in the rainfall records (for example in P_h around 1000 GMT) may be regarded as mesoscale variability. Since the two gauges were not in line along wind this feature cannot necessarily be expected to appear in both records. Hence the area of heavier rain that affected the coastal site around 1500 GMT (and resulted in a negative enhancement for a short time) is not discernible in the record from the hill gauge. The open circles in Fig. 14 give the predictions from the Bader and Roach model, i.e. taking account of the variation of both P_0 and the 600 m wind speed (for intermediate times the wind speeds were obtained by linear interpolation between the sonde ascents). A reasonable fit to the observed variation of P_h is obtained but this deteriorates after 1400 GMT.

Hill *et al.* (1981) identified various factors that could influence the relationship between theoretical and actually observed enhancements. As noted earlier, hill slope is important and the steeper slopes in the Mountains of Mourne should have generated greater enhancement, as was in fact observed. The assumptions made in the model may also underestimate the wind speed near the ground over the hills and greater speeds would increase the vertical component of air motion, produce higher condensation rates and so greater rainfall enhancements.

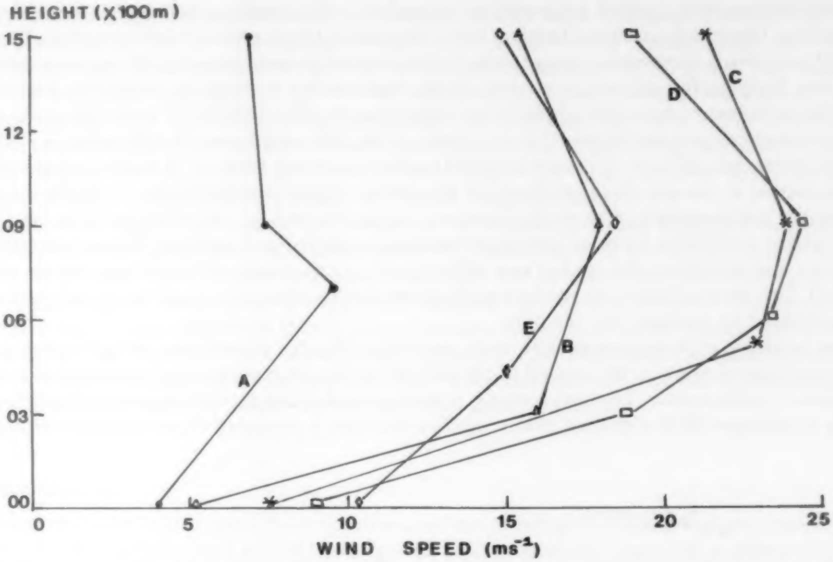


Figure 13. Variation of the wind speed in the lowest 1.5 km on 27 December 1978. Profile times are: A, 0001 GMT; B, 0600 GMT; C, 1200 GMT; D, 1800 GMT; and E, 2359 GMT.

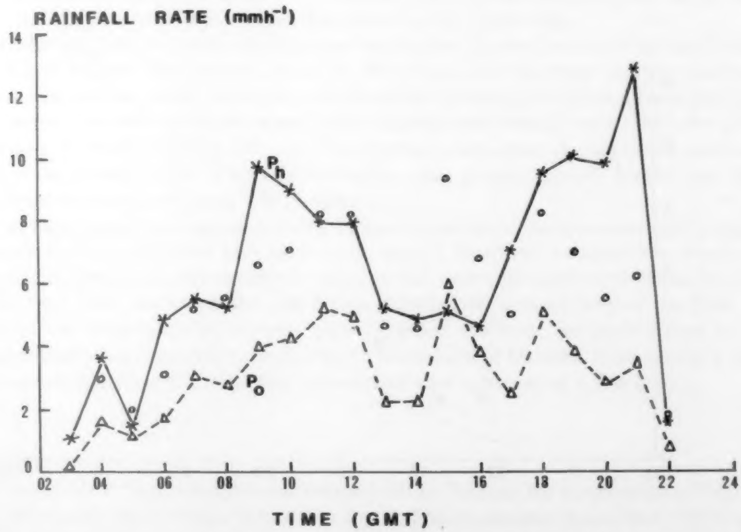


Figure 14. Variations of mean hourly rainfall rates in the hills (P_h, rain-gauge site 3) and at the coast (P_0, rain-gauge site 1). The data points are plotted at the ends of the hours to which they refer. Open circles are the predicted rainfall rates in the hills from the model of Bader and Roach (1977).

Potential instability (which is ignored in the model) is also usually prevalent in strong enhancement situations. This usually occurs in bands at lower and middle levels, although in this instance (see Fig. 5) it would seem that a progressive change from middle-level PI to more extensive PI from the surface to 700 mb was likely as the depression moved slowly northwards. It could be, therefore, that the larger differences between observed and predicted enhancements after 1400 GMT were due to the release of fairly widespread and significant PI in the vicinity of the hills, as proposed by Browning *et al.* (1974). As noted earlier, it is difficult to obtain large enhancements (about 6 mm h^{-1}) without increased rates of condensation in the cap cloud produced by the release of potential instability. Towards the end of 27 December enhancements of close to 10 mm h^{-1} were observed on this occasion (Fig. 14).

A further possibility for poor agreement between predicted and observed enhancements is that P_0 does not approximate to the rainfall rate at the top of the cap cloud (which is the parameter used in the model). This seems likely to be the case in instances, such as that considered here, where PI may have been released by passage over the hills.

The variation of enhancement with wind speed (ignoring the dependence on P_0) is given in Fig. 15. Since the coastal site was not upwind of the hills the enhancements have been averaged over two-hour periods to reduce scatter. The data certainly suggest a wind-speed dependence not unlike that observed in the Glamorgan Hills, although clearly significant scatter is produced by the variations in P_0 apparent

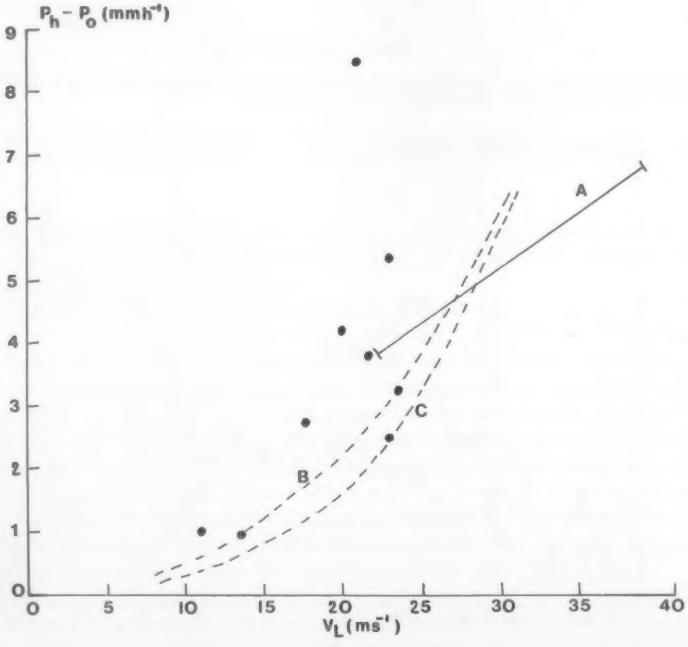


Figure 15. Variation of the rainfall enhancement ($P_h - P_0$) with the 600 m wind speed (V_L). Line A is from Nash and Browning (1977) (20 cases from 1960 to 1974), line B is from Hill (1977) (40 cases, 1974/5) and line C is from Hill *et al.* (1981) (8 cases, 1976/7).

in Fig. 14 (i.e. the larger enhancements are also associated with large P_0 values). However, for wind speeds in the range 10–15 m s^{-1} it would seem that $P_h - P_0$ is about 1 mm h^{-1} and that to achieve really substantial increases of rainfall rates in the hills, wind speeds of the order of 20–25 m s^{-1} are required.

There is a noticeable departure in Fig. 15 of the enhancements from the South Wales behaviour at larger wind speeds. These points arise from the data between 1900 and 2100 GMT in Fig. 14 and could well be due to the fact that P_0 at this time is no longer representative of the rainfall rate at the top of the cap cloud, owing to the release of PI in the vicinity of the hills. Nevertheless, even the behaviour at low wind speeds is more marked than the Bader and Roach model predicts.

Hill *et al.* (1981) suggest that some reformulation of the physical processes leading to enhancement may be required and Carruthers and Choularton (1982) draw attention to the low-level jet usually present in major enhancement situations. Deep moist jets will produce thick cap clouds and hence greater enhancement. It could be that the 'apparent' sensitivity of the enhancement to wind speed arises from the fact that the strongest wind speeds are associated with the most active systems which in turn have well-defined jets that form thick cap clouds. However, this possibility does not seem applicable to the cases considered by Hill *et al.* (1981) since the radar observations confirmed that enhancement was limited to a fairly shallow zone above the hill (less than about 1.5 km).

Concluding remarks

The event described in this paper was exceptional in that prolonged moderate to heavy rainfall over low ground in the eastern parts of Northern Ireland was significantly enhanced in hilly areas. This produced a fall at the Silent Valley of 245 mm in 56 hours, which has an expected frequency of occurrence of less than once in 1000 years. At higher levels the precipitation turned to snow early on 28 December and equivalent rainfall totals are not available. However, as noted earlier it seems likely that these exceeded 300 mm at the 300 m level in the central area of the hills.

From the forecasting viewpoint this investigation emphasizes the need to assess the likely importance or orographic effects in particular synoptic contexts. With moist flow and light winds it would seem that enhancements are likely to be small. However, with the combination typical of an intense depression, i.e. strong winds, moist low-level flow and appreciable background rainfall rates, then the effects may indeed be dramatic. Rainfall totals in hilly areas exposed to winds from the sea could easily be two or three times those at nearby coasts. This will inevitably mean greater run-off, higher river levels and increased flooding risk in downstream low-lying areas.

This paper has highlighted one extreme member of a set of similar occurrences currently being analysed in which enhancement occurs in the hilly areas in the east of Northern Ireland when winds are in the south-east quadrant. Similar events doubtless occur in the west and north-west of the Province with moist south-westerly flow, although the protection afforded by upwind hills of the Irish Republic probably reduces the occurrence of extreme events. Hence, the most susceptible area in Northern Ireland to exceptionally heavy rainfall is probably the Mountains of Mourne. If the synoptic situation is slow moving remarkable rainfall totals may accumulate over a period of a few days.

Acknowledgements

Thanks are due to Mr P. Eastwood (Meteorological Office, Belfast) for preparation of Fig. 10 and to Mr F. Wright (Meteorological Office, Belfast) for Fig. 9. Thanks are also due to Met O 9b (outstations investigations section) for the supply of plotted charts and radiosonde data and to Mr R. M. Morris, Mr F. Singleton, Mr F. F. Hill, Dr K. A. Browning, Mr J. Findlater and Dr W. T. Roach, for useful comments and suggestions.

References

Bader, M. J. and Roach, W. T. 1977 Orographic rainfall in warm sectors of depressions. *Q J R Meteorol Soc*, **103**, 269–280.

Bergeron, T. 1965 On the low-level redistribution of atmospheric water caused by orography. Proceedings of the International Conference on Cloud Physics, May 24–June 1, 1965, Tokyo and Sapporo. Supplement, 96–100.

Browning, K. A. 1980 Structure, mechanism and prediction of orographically enhanced rain in Britain. WMO-ICSU, Orographic effects on planetary flows. GARP Publications Series No. 23, 85–114.

Browning, K. A. and Pardoe, C. W. 1973 Structure of low-level jet streams ahead of mid-latitude cold fronts. *Q J R Meteorol Soc*, **99**, 619–638.

Browning, K. A., Hill, F. F. and Pardoe, C. W. 1974 Structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. *Q J R Meteorol Soc*, **100**, 309–330.

Browning, K. A., Hardman, M. E., Harrold, T. W. and Pardoe, C. W. 1973 The structure of rainbands within a mid-latitude depression. *Q J R Meteorol Soc*, **99**, 215–231.

Carruthers, D. J. and Choularton, T. W. (1983) A model of the feeder seeder mechanism of orographic rain including stratification and wind drift effects. (Submitted to *Q J R Meteorol Soc*.)

Hill, F. F. 1977 On forecasting rainfall at Llyn Fawr over periods of a few hours. (Unpublished, copy available at Meteorological Office Radar Research Laboratory, Malvern.)

Hill, F. F., Browning, K. A. and Bader, M. J. 1981 Radar and raingauge observations of orographic rain over south Wales. *Q J R Meteorol Soc*, **107**, 643–670.

Jack, W. L. 1981 Rainfall return periods for December 1979. *Weather*, **36**, 274–276.

Kreitzberg, C. W. 1968 The mesoscale wind field in an occlusion. *J Appl Meteorol*, **7**, 53–67.

Nash, J. and Browning, K. A. 1977 Structure of the lower atmosphere associated with heavy falls of orographic rain. (Unpublished, copy available in National Meteorological Library, Bracknell.)

Pedder, M. A. 1979 Vertical cross-section analysis based on a cylindrical projection. *Weather*, **34**, 258–265.

Pedgley, D. E. 1970 Heavy rainfalls over Snowdonia. *Weather*, **25**, 340–350.

Notes and news

Building and Construction Climatology Unit

Since 1975 a small unit within the Climatological Services Branch of the Meteorological Office has assisted with the weather-related problems encountered by researchers at the Building Research Establishment (BRE), by staff of other government departments and, to a lesser extent, by the building industry at large. The two posts in this Unit have been funded by BRE. Foremost among the collaborative projects undertaken with BRE have been studies of wind-driven rain, extreme values of snow depth and wind speed, and rainfall during the working day. The Unit has also contributed to the preparation of a pilot booklet *Weather and building operations in the Plymouth region* containing various summaries of weather data pertinent to outdoor construction work.

Financial arrangements for the Unit have been revised recently and, although strong links will be maintained with BRE, it will now be possible for the Unit to expand its activities in the field of Meteorological Office services for the building and construction industries. Efforts will be made to develop climatological services relevant to the needs of those industries, as well as publicizing those services already available. The first promotion by the new Unit, organized jointly with the Public Services Branch, was at the six-day London Building Exhibition at Earls Court last October, during which Meteorological Office services were publicized using a film, simulated forecasting work bench, Prestel and extensive display material.

Requests for information about climatological services for the construction industry may be directed to: Building and Construction Climatology Unit
Meteorological Office Met O 3
London Road
Bracknell
Berkshire
Telephone: 0334-20242 Ext. 2299

International Symposium on Building Climatology

The Central House of Architects in Moscow was the venue for a Building Climatology Symposium which was held from 20–23 September 1982 under the auspices of the International Council for Building Research Studies and Documentation (CIB), the World Meteorological Organization (WMO) and various Soviet organizations. There were over 200 delegates, including 35 from outside the Soviet Union. Twenty-one countries were represented mainly by building science researchers, climatologists, architects and engineers; the six United Kingdom delegates came from the Meteorological Office, the Building Research Establishment, the Welsh School of Architecture (2), Heriot-Watt University and the Northern Ireland Federation of Housing Associations.

The main part of the symposium consisted of three simultaneous technical sessions, during which 40 papers were presented. These dealt with:

(i) climate and architectural-building design,
(ii) methods of obtaining and presenting climatic information for building design, and
(iii) problems of insolation and sun control of buildings and city territory.

Criticisms which could be levelled at several of these papers are that they were too familiar, or too general, or too badly presented to raise significantly the level of awareness of the delegates. The published proceedings of the symposium should overcome the last-named criticism.

The technical sessions were preceded and followed by plenary sessions at which representatives of the organizing bodies spoke, including Professor Drozdov (Head of USSR Research Institute of Building Physics), Professor Sebastyen (CIB Secretary-General) and Dr Jovicic (Chief, Industrial Applications and Climatology Branch, WMO).

There were technical excursions to a large, high-density housing development and to the Research Institute of Building Physics, where the facilities include an impressive artificial sky vault and climatic laboratories where building components intended for use in the USSR are subjected to temperatures as low as –50 °C.

After the end of the symposium, a meeting of the CIB Working Commission W71 (Building Climatology) was attended by about 15 delegates. During this meeting there were interesting discussions about the limits of the Commission's competence and about a review of current research carried out recently by W71.

The symposium should be judged as a success, not perhaps when one considers the utility of some of the papers presented, but certainly because of the international (and national) links which were forged or renewed during the week. The organizing committee are to be congratulated on their efforts to ensure the smooth running of the various sessions and excursions. Even the weather had been arranged perfectly, because Moscow was enjoying an 'Indian summer' with prolonged sunshine and daytime temperatures around 20 °C.

M. J. Prior

Falklands conflict (operation CORPORATE): honours and awards for Meteorological Office staff

The Director-General held a reception at Headquarters on Monday 18 October 1982 for staff who had been involved in the Falklands conflict from April to July. The South Atlantic Campaign Medal was presented personally to six members of the Mobile Meteorological Unit who were available out of the ten who had qualified for the medal through their service on Ascension Island. The remaining four were currently serving either at Ascension Island or at RAF Port Stanley. The Director-General also congratulated Mr J. Turner, who had received the MBE for his work in bringing the 15-level model into service to cover the South Atlantic and South America some four months ahead of schedule, and Mr W. McQueen, Senior Meteorological Officer at RAF Coningsby, who had received the MBE for his service as Officer Commanding in his reserve rank of Squadron Leader in the Royal Air Force Reserve of Officers, when the Mobile Meteorological Units were first established on Ascension Island and later at Port Stanley airfield. The Director-General also presented letters of commendation from the Permanent Under-Secretary of State to five staff who had been involved with the Falklands conflict either through their service with the Mobile Meteorological Units or in Headquarters support. The reception was attended by members of the Directorate and by Group Captain M. Burton, DD Ops (Nav)(RAF), representing the Air Staff.

The following staff received honours, the South Atlantic Campaign Medal or letters of commendation:

MBE

W. R. McQueen	Senior Scientific Officer	Senior Meteorological Officer, RAF Coningsby.
J. Turner	Senior Scientific Officer	Operational Numerical Analysis and Forecasting Branch, Headquarters Bracknell.

The Director-General of the Meteorological Office's reception for staff who were involved in operation CORPORATE. Back row, from left to right: J. Turner, Squadron Leader W. R. McQueen, Flight Lieutenant P. W. Davies, Sir John Mason, Squadron Leader H. Pettit (ex Officer-in-charge of the Mobile Meteorological Unit, now retired) and Group Captain M. Burton. Front row, from left to right: R. S. Bell, Flying Officer S. W. Galaud, Flight Lieutenant B. Phillips, Flying Officer R. G. Adam, E. E. Williams and Squadron Leader K. J. Maidment.

South Atlantic Campaign Medal

R. G. Adam	Scientific Officer	Kirkwall.
P. W. Davies	Higher Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
S. W. Galaud	Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
D. R. Kingham	Scientific Officer	RAF Northolt.
K. J. Maidment	Senior Scientific Officer	Headquarters Strike Command.
W. R. McQueen	Senior Scientific Officer	Senior Meteorological Officer, RAF Coningsby.
B. Phillips	Higher Scientific Officer	London Weather Centre.
J. H. Philpott	Higher Scientific Officer	Meteorological Office College.
C. G. Robins	Scientific Officer	RAF Marham.
D. J. Wheeler	Scientific Officer	Headquarters Strike Command.

Letters of Commendation

R. S. Bell	Senior Scientific Officer	Operational Numerical Analysis and Forecasting Branch, Headquarters Bracknell.
P. W. Davies	Higher Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
S. W. Galaud	Scientific Officer	Observational Requirements and Practices Branch, Headquarters Bracknell.
B. Phillips	Higher Scientific Officer	London Weather Centre.
E. E. Williams	Higher Scientific Officer	Defence Services Branch, Headquarters Bracknell.

Review

Climate, history and the modern world, by H. H. Lamb. 154 × 233, pp. xix + 387, *illus.* Methuen & Co. Ltd., London, New York, 1982. Price £8.95.

Professor Lamb's latest book, though it follows to some extent the general pattern of his *magnum opus* (Climate: present, past and future; Methuen, 1972 & 1977), is by no means a mere abridgment of that massive work but is an essentially new book, designed and written for the educated general reader; the relative amount of space allotted to various topics is, for example, quite different. Two brief introductory chapters are followed by three on 'the development of climate' including discussions of the general circulation and methods of reconstructing past climates, eight on 'climate and history', and five on 'climate in the modern world and questions over the future'.

The author gives, as he usually does, an interesting and readable account of what has now been discovered of the history of the world's climate, concentrating chiefly on the recent post-glacial period — which of course includes the whole development of human civilization out of the palaeolithic. The book is probably weakest on applications of principles of physical science and statistics to the discussion of known or suspected causes of climatic variation. For example, it would have been interesting to have had at least some discussion of how the present arid climate of the Sahara and the much moister climate of only 5000 or so years ago can both be made consistent with the necessary dynamical and energetic constraints of the general circulation of the atmosphere, or how the presence of volcanic dust affects the

partitioning of incident solar radiation between the direct, diffuse, and reflected components. Questions are begged here and there: for example, the decline of Petra (p. 150) is much more likely to have been due to military and economic causes — particularly the rise of Palmyra as a dominant trading centre — than to climatic ones.

The referencing of the book is oddly inconsistent. Some sections are liberally supplied with detailed references for the statements and opinions quoted while others are quite free of such necessary aids to the critical reader. See, for example, figures 90–92.

R. P. W. Lewis

NERC Automatic Weather Station Pool

The Natural Environment Research Council (NERC) have asked us to print the following announcement of a facility which NERC Scientific Services are making available to interested users:

Automatic weather station equipment pool

General

An equipment pool of battery-operated automatic weather stations (AWS) has been set up by the Natural Environment Research Council.

These stations are maintained by the Institute of Hydrology (IH), Wallingford and are offered on free loan to assist approved research projects at NERC institutes and at institutions of higher education. Standard data processing, which consists of a hard copy listing of hourly and daily totals or averages, is provided free of charge.

The AWS Pool is supervised by a small management committee which reports to the Director, NERC Scientific Services (NSS). The committee is chaired by Professor J. B. Thornes of Bedford College.

Equipment

AWS equipment has been developed to meet IH's own research needs, often involving detailed measurement of climate at unmanned remote sites where access is difficult and where electricity is rarely available.

The weather station's three-metre mast supports six sensors: solar radiation, net radiation, wind run, wind direction, air temperature and wet-bulb depression. A ground level rain-gauge completes the station. The sensors are connected via plugs and sockets to a junction box which is provided with extra entry ports for further sensors if required.

Sensor outputs are logged on standard cassettes by the Microdata miniature data logger and interface unit which were designed specifically for weather station data logging. Either the cassette or, if preferred, the complete logger may be changed at the end of the sampling period, normally at two-week intervals. The logger has 11 channels of which 7 are used for the weather station; the remainder are available for monitoring other variables. Use of the spare channels is at the discretion of the user in consultation with the Pool staff. At present, data from these spare channels cannot be processed and would have to be presented as raw data.

Conditions of loan

Borrowers must be able to demonstrate their ability to carry out operational procedures and simple checks on the equipment to be loaned. In the case of equipment set up outside the UK, some additional

training (½–1 day) may be necessary. Training is provided by Pool staff and operators should make the necessary arrangements well in advance of the loan period. Site visits by Pool staff can be arranged and the cost may be charged, by prior agreement, to the institution borrowing the equipment.

All borrowers are required to sign a form on which their institution agrees to indemnify Council to the full amount of any loss or damage to equipment arising from any cause whatsoever (deterioration through normal wear and tear excepted). Borrowers are notified of the full replacement value of the equipment listed in their loan application. Borrowers other than publicly funded bodies must provide proof of appropriate insurance.

Borrowers must advise NSS at the earliest opportunity should the return of the equipment, in good working order, on the expiry of the loan period be in any doubt. Except for deployment within the UK borrowers are responsible for collection from and return to the Pool of all equipment borrowed; within the UK IH staff will be responsible for installation and collection. An account of any repairs undertaken on an overseas project must be presented with the returned equipment.

As soon as possible after completion of the project borrowers are required to furnish the management committee with a brief report on equipment performance and also on scientific results. A copy of subsequent reports or publications should be forwarded to NSS.

Council reserves the right to withdraw Pool equipment should exceptional circumstances require this.

Local applications

All applicants are required to submit an application form, which may be forwarded at any time, for consideration by the Management Committee. Application forms are available from:

Natural Environment Research Council
NERC Scientific Services
Polaris House
North Star Avenue
Swindon
Wilts
SN2 1EU
Telephone (0793) 40101 Ext. 335

Applicants for equipment loans who are also seeking research grant support from NERC should, separately, submit the NERC research grant application form (RG1) in the normal way (see Research Grants booklet). Failure to gain a research grant will not in itself preclude an equipment loan.

Further details may be obtained from Dr R. R. Gatten at the above address or from Dr T. J. Dean at the NERC Institute of Hydrology, Wallingford, Oxon, OX10 8BB, Tel: (0491) 38800.

B. F. Rule
Director
NERC Scientific Services

THE METEOROLOGICAL MAGAZINE

No. 1330 May 1983 Vol. 112

CONTENTS

	Page
The work of the Boundary Layer Branch of the Meteorological Office. C. J. Readings, P. J. Mason and F. B. Smith	109
Exceptional orographic rainfall in the Mountains of Mourne, S. J. Caughey and S. J. G. Partington	125
Notes and news	
Building and Construction Climatology Unit	143
International Symposium on Building Climatology	143
Falklands conflict (operation CORPORATE): honours and awards for Meteorological Office staff	144
Review	
Climate, history and the modern world. H. H. Lamb. *R. P. W. Lewis*	146
NERC Automatic Weather Station Pool	147

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell RG12 2SZ and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Applications for postal subscriptions should be made to HMSO, PO Box 569, London SE1 9NH.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full-size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd. 24-28 Oval Road, London NW1 7DX, England.

Please write to Kraus Microfiche, Rte 100, Millwood, NY 10546, USA, for information concerning microfiche issues.

Printed in England by Robendene Ltd, Amersham, Bucks.
and published by
HER MAJESTY'S STATIONERY OFFICE

£2 monthly

Annual subscription £26.50 including postage

Dd 736047 C15 5/83

ISBN 0 11 726934 4
ISSN 0026-1149